TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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On-Board Electronic Control Systems of Future Automated Heavy Machinery

Julkaisu 1352 • Publication 1352

Tampere 2015

Tampereen teknillinen yliopisto. Julkaisu 1352
Tampere University of Technology. Publication 1352

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Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Sähkötalo Building, Auditorium S2, at Tampere University of Technology, on the 4th of December 2015, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2015

ISBN 978-952-15-3636-6 (printed)
ISBN 978-952-15-3649-6 (PDF)
ISSN 1459-2045

Abstract

The level of automation and wireless communication has increased in heavy machinery recently. This requires utilizing new devices and communication solutions in heavy machinery applications which involve demanding operating conditions and challenging life-cycle management. Therefore, the applied devices have to be robust and hardware architectures flexible, consisting of generic modules. In research and development projects devices that have various communication interfaces and insufficient mechanical and electrical robustness need to be applied. Although this thesis has its main focus on machines utilized as research platforms, many of the challenges are similar with commercial machines.

The applicability of typical solutions for data transfer is discussed. Controller area network with a standardized higher level protocol is proposed to be applied where data signalling rates above 1 Mb/s are not required. The main benefits are the availability of robust, generic devices and well-established software tools for configuration management. Ethernet can be utilized to network equipment with high data rates, typically used for perception. Although deterministic industrial Ethernet protocols would fulfil most requirements, the conventional internet protocol suite is likely to be applied due to device availability.

Sometimes sensors and other devices without a suitable communication interface need to be applied. In addition, device-related real-time processing or accurate synchronization of hardware signals may be required. A small circuit board with a microcontroller can be utilized as a generic embedded module for building robust, small and cost-efficient prototype devices that have a controller area network interface. Although various microcontroller boards are commercially available, designing one for heavy machinery applications, in particular, has benefits in robustness, size, interfaces, and flexible software development. The design of such a generic embedded module is presented.

The device-specific challenges of building an automated machine are discussed. Unexpected switch-off of embedded computers has to be prevented by the control system to avoid file system errors. Moreover, the control system has to protect the batteries against deep discharge when the engine is not running. With many devices, protective enclosures with heating or cooling are required.

The electronic control systems of two automated machines utilized as research platforms are presented and discussed as examples. The hardware architectures of the

control systems are presented, following the proposed communication solutions as far as is feasible. Several applications of the generic embedded module within the control systems are described. Several research topics have been covered utilizing the automated machines. In this thesis, a cost-efficient operator-assisting functionality of an excavator is presented and discussed in detail.

The results of this thesis give not only research institutes but also machine manufacturers and their subcontractors an opportunity to streamline the prototyping of automated heavy machinery.

Preface

I am grateful to professors Kalevi Huhtala and Matti Vilenius for providing excellent research facilities for automated heavy machinery as well as for their guidance at the Department of Intelligent Hydraulics and Automation. Also, I wish to thank the entire staff of the department, not forgetting the many old colleagues working outside the university nowadays, for creating an inspiring and supportive environment for research. Especially, I express my gratitude for valuable discussion and feedback to the people who have been working in the same office with me during the past decade: Miika Ahopelto, Joni Backas, Ji-Wung Choi, Reza Ghabcheloo, Tomi Krogerus, Erkki Lehto, Jarno Uusisalo, Jani Vilenius, and Antti Vuohijoki.

In addition, I wish to thank Ville Ahola, Janne Honkakorpi, Mikko Huova, Mika Hyvönen, Seppo Joonala, Sanna Järvensivu, Antti Kolu, Juha Kukkohovi, Markku Luomaranta, Jussi Tervonen, and Vesa Ulvila for fruitful teamwork in designing, building, and utilizing the equipment discussed in this thesis.

The valuable pre-examination feedback from professors Marcus Geimer and Kari Tammi is highly appreciated.

Part of this research was funded by TUT Graduate School. The research was conducted partially in the Centre of Excellence in Generic Intelligent Machines Research funded by the Academy of Finland. Part of the research was also conducted in the Energy and Life Cycle Cost Efficient Machines (EFFIMA) research program, managed by the Finnish Metals and Engineering Competence Cluster (FIMECC), and funded by the Finnish Funding Agency for Technology and Innovation (TEKES), research institutes and companies. Their support is gratefully acknowledged. Furthermore, I wish to express my gratitude for financial support to the Jenny and Antti Wihuri Foundation, the Finnish Science Foundation for Economics and Technology as well as the Finnish Foundation for Technology Promotion.

Although I consider prototyping with automated heavy machinery to be very rewarding, I am grateful for my family and friends, as well. I wish to thank my parents, Heikki and Liisa, for encouraging me to consider doctoral studies. Most of all, I wish to express my gratitude to Maija, Oliver, and Aada for their love, support, and understanding. After all, “Mum is a teacher and dad repairs stuff”.

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List of Symbols

θ_1	angle measured by boom inclinometer	[°]
θ_2	angle measured by stick inclinometer	[°]
θ_3	angle measured by bucket inclinometer	[°]
θ_{bucket}	bucket joint angle	[°]
θ_{stick}	stick boom joint angle	[°]
e_{tot}	total error	[%]
e_{slew}	relative error in slew position	[%]
e_{boom}	relative error in base boom position	[%]
e_{stick}	relative error in stick boom position	[%]
e_{bucket}	relative error in bucket position	[%]
R_t	network throughput	[b/s]
R_b	data signalling rate	[b/s]
T_d	length of payload data	[b]
T_{fs}	length of frame slot	[b]

List of Abbreviations

10BASE-T	Ethernet at 10 Mb/s in twisted pairs of copper wire
100BASE-TX	Ethernet at 100 Mb/s in twisted pairs of copper wire
1000BASE-T	Ethernet at 1 Gb/s in twisted pairs of copper wire
4G	fourth generation (of mobile telecommunications technology)
6DOF	six degrees of freedom
8P8C	eight position eight contact (modular connector)
AC	alternating current
ADC	analogue-to-digital converter
AFS	articulated-frame steering
AGV	autonomous guided vehicle
AP	access point (of a wireless network)
API	application programming interface
ARP	address resolution protocol
ATX	Advanced Technology eXtended (computer form factor)
BIOS	basic input output system
CAN	controller area network
CAN FD	CAN with flexible data-rate
CiA	CAN in Automation
CIP	Common Industrial Protocol
CRC	cyclic redundancy check
DAC	digital-to-analogue converter
DARPA	Defense Advanced Research Projects Agency
DC/DC	direct current to direct current
DFCU	digital flow control unit
DGPS	differential Global Positioning System
DIP	dual inline package
DSP	digital signal processor
EBX	Embedded Board, eXpandable (computer form factor)
EGNOS	European Geostationary Navigation Overlay Service
EOnCE	Enhanced On-Chip Emulation
EPIC	Embedded Platform for Industrial Computing (computer form factor)
FPGA	field-programmable gate array
FPU	floating-point unit
GLONASS	Global Navigation Satellite System (the particular system maintained by Russian Aerospace Defence Forces)
GNSS	global navigation satellite system (in general)
GPIO	general purpose input-output
GPS	Global Positioning System (the particular system maintained by U.S. Air Force)
HDL	hardware description language
I^2C	Inter-IC (digital interface)
IC	integrated circuit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IMU	inertial measurement unit
I/O	input-output
IP	internet protocol

ISO	International Organization for Standardization
JTAG	Joint Action Test Group
LAN	local area network
LED	light-emitting diode
LIN	Local Interconnect Network
MEMS	micro electrical mechanical system
NMEA	National Marine Electronics Association
Ntrip	Networked Transport of RTCM via Internet Protocol
ODVA	ODVA, Inc. (formerly Open DeviceNet Vendors Association, Inc.)
OSI	Open Systems Interconnection
PDO	Process Data Object
PID	proportional-integral-derivative
PLC	programmable logic controller
PoE	Power over Ethernet
PPS	pulse per second
PTP	precision time protocol
RAM	random access memory
RJ45	registered jack 45
PWM	pulse width modulation
RTCM	Radio Technical Commission for Maritime Services
RTK	real-time kinematic
SAE	SAE International (formerly Society of Automotive Engineers)
SDI	Serial Digital Interface
SIP	single inline package
SPI	serial peripheral interface
SSD	solid state drive
TCP	transmission control protocol
UDP	user datagram protocol
UPS	uninterruptible power supply
USB	Universal Serial Bus
UWB	ultra wide band
VRS	Virtual Reference Station

1 Introduction

The constant development in heavy machinery aims at higher efficiency, easier and more comfortable operation and lower maintenance costs. These goals can be reached by increasing the level of automation and implementing sophisticated operator-assisting functions. These functions have already been introduced in many fields of heavy machinery. There are even autonomously navigating and operating machines available for certain applications. According to Prescott, the development is likely to continue and cover more and more fields of heavy machinery. This is predicted to have a substantial effect on the market, eventually. [90] Meanwhile, utilizing another disruptive technology, the Industrial Internet, or the Internet of Things, also requires similar equipment to be installed on manually operated machines.

1.1 Background

Traditionally, the control systems of hydraulic heavy machinery have consisted of mechanical and hydraulic components. With machines like these, design, production, maintenance and spare parts service can be straightforward. Even several decades after the original machine was built, spare parts can be manufactured according to original drawings by a number of subcontractors.

As the level of automation is increased, electronic devices are required. The machines are typically still designed to have life cycles of decades. Because electronic components typically have much shorter life cycles, there are new challenges in design, production, maintenance and spare parts service. These challenges are even greater when the control system has devices that are not widely used in heavy machinery, have neither standardized nor well-established interfaces and may be available from only one manufacturer. These devices may have originally been developed for the office environment, service robotics, factory automation or land surveying, for example.

Regardless of the level of automation, it is common that several machines are operated at the same working site. These machines can perform individual tasks or co-operate. In either case, multi-machine environments set new requirements for control systems of automated heavy machinery to maintain efficiency and safety.

In this thesis, the design perspectives and challenges concerning control systems of automated heavy machinery are examined. The applicability of various devices and communication technology related to automated functionality is discussed considering modularity and robustness. The challenges related to different bus and network technologies and different types of devices are reviewed. Two examples of an on-board control system of automated heavy machinery for multi-machine environment are presented and discussed.

1.2 Scope of thesis

The control systems of automated heavy machinery discussed in this thesis are primarily for research and development but also applicable to commercial future machinery to a great extent. The discussion applies to autonomous machines but also more common applications where the control system performs operator-assisting functions, remote monitoring or data logging.

The term ‘mobile machinery’ is used in this thesis to describe wheeled and tracked heavy machinery, typically equipped with either a fixed tool or a removable attachment. The discussion in this thesis applies to mobile machines, in particular.

The mobile machines that are presented as examples of automated heavy machinery in Chapter 6 and Chapter 7 are designed and built for research and development. They are operated in closed environments under immediate human supervision. The machine safety required of commercial machinery by legislation is not considered in this thesis.

Although the machines of the presented automated machinery cases are research platforms, they have much in common with commercial mobile machines. This applies to operating environment, maintenance and upgrades, for example. Therefore, many of the results are also applicable to designing the control systems of commercial automated mobile machines.

1.3 Related research

There has been active publishing in the field of automated mobile machines since the 1990s. The machines that are discussed in most publications have been built as proof-of-concepts or for use as research platforms. Control system architecture and hardware are, however, usually neither described nor discussed in detail and the emphasis is often on control algorithms and performance. The automated machines that are most comprehensively discussed in the literature, and therefore covered by this section, are developed for cargo handling, agriculture, mining and earth-moving applications. This section also covers research on automated off-road capable vehicles with advanced sensing and computing, often targeted at military applications.

1.3.1 Systems integration and management over machine life cycle

Saha proposes several methods to improve the life cycle manageability of electronic control systems. These apply to hydraulic mobile machines with conventional digital and analogue inputs and outputs, especially. The methods include extending the scale of controller area networks (CAN) with switches and splitting the electronic hardware platform into a logical and a physical platform. Then the logical architecture, that is, the functionality of the control system, could be implemented and maintained in hardware description languages (HDL), independent of the physical platform. [99]

To enable this, in-system reconfigurable mixed-signal hardware is required. Saha also demonstrates that a physical platform like this can be designed and built. The example platform has a field-programmable analogue integrated circuit (IC) which is used to implement reconfigurable analogue-to-digital converters (ADC). [99]

Uusisalo compares distributed and centralized computation in small, remote-controlled wheel loaders. Two machines developed to be used as research platforms are used as examples. It is concluded that although distributed computation has the benefits of modularity and flexibility, a complex application may also require some centralized computation. An approach where the simple control tasks of an automated machine are computed by the devices of the actuator layer is suggested. [121]

1.3.2 Electronic control systems in automated cargo handling

Durrant-Whyte describes an autonomous guided vehicle (AGV) that has been developed for transporting cargo containers in a port environment. The AGV has a hydrostatic power transmission with a constant speed diesel engine, a variable-displacement pump and variable-displacement hub motors. Steering is also realized with hydraulics. The low-level control of the hydraulic system is implemented using proprietary control units that can perform proportional-integral-derivative (PID) control. Since the platform does not have a suspension system, the protective central computer housing is suspended. Pose estimation, i.e. solving the position and orientation, and obstacle detection is done with two horizontally scanning radars, one mounted on each end of the AGV. The steering angles and angular velocities of the wheels are measured with encoders. The computing platform is presented in Figure 1. [27]

The platform is modular at IC level, consisting of 11 transputers [110]. Furthermore, there is a digital signal processor (DSP) for both radars and an on-board computer for hosting the transputer network, monitoring the vehicle and accessing the wireless link. The transputers that are labelled T420 only perform integer arithmetic in the hardware, while the T805s have floating-point units (FPU). A special-purpose interface card with 42 measurement channels is used to measure hydraulic pressures, oil temperature, bumper limit switches, top-deck load and diesel speed for safety and condition monitoring. This functionality is independent of the rest of the control system. Moreover, every transputer has a separate status output that triggers an emergency stop if a software or hardware fault occurs. Transputer technology is chosen because it enables flexible input-output (I/O) configurations and there is software support for parallel processing on single and multiple processors. Durrant-Whyte states that the chosen transputer architecture makes both hardware and software development very efficient. Unfortunately, the project also demonstrates the short and unpredictable production life-cycles of ICs: transputers became obsolete soon after the results of the project were published. [27]

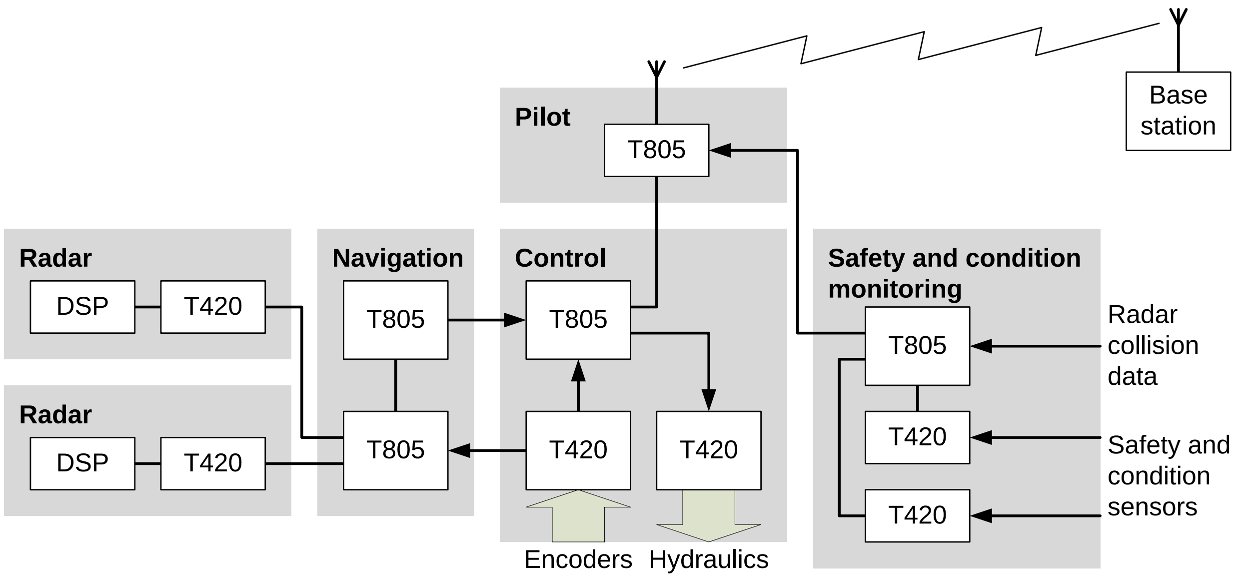

Figure 1. Modular computing platform of the AGV, adapted from [27].

More complex automated machines have also been developed for cargo handling. Durrant-Whyte et al. present an automated eight-wheeled straddle carrier, AutoStrad. The machine (Figure 2) is based on a manually operated straddle carrier. Both straddle legs of the prototype machine have a diesel engine with a semi-automatic gear box. The machine has hydraulic all-wheel steering and load lifting. The four wheels of each straddle leg are mechanically linked to produce symmetric steering. The actuators and sensors are connected to a programmable logic controller (PLC) via CAN. The PLC monitors and regulates vehicle health based on hydraulic pressures and oil temperature, for example. The functional architecture of the control system is rather similar to the previously described AGV, but the hardware of the control system is different. The system controls the engines, gear boxes, steering, brakes, hoist and lights of the machine. [28]

Figure 2. An automated straddle carrier, AutoStrad. [28]

A high-integrity navigation system is implemented with a horizontally scanning radar, four wheel encoders, one encoder in the steering system of each straddle leg, a real-time kinematic (RTK) global navigation satellite system (GNSS) receiver and an inertial measurement unit (IMU). AutoStrad also has four horizontally scanning lidars, one at each end of each straddle leg, for obstacle detection. Next to each lidar is a mechanical bumper with a limit switch. The system has a receiver for a heart-beat radio signal and another radio link for receiving tasks and plans from the base station. Although the computing platform, sensor interfaces and on-board networking are not described in detail, it is mentioned that a separately housed computer operates the on-board safety system. After thorough testing of the first prototype, four AutoStrads were built for testing fleet operation. The hardware of the control system was redesigned, and machine-level control functionality was implemented by the manufacturer of the original straddle carrier. Nevertheless, the system design was not changed from the first prototype of AutoStrad. Finally, the commercial version of AutoStrad was designed to have a series hybrid drivetrain and on-board networking based exclusively on CAN. [28]

Teller et al. have developed an automated forklift that can be operated safely and flexibly alongside humans both outdoors and indoors. Although the control system is intended for short proof-of-concept demonstrations in gentle environmental conditions, the hardware architecture containing several real-time sensors with high data rates makes the project relevant to this study. The forklift is modified from a commercial manually operated machine. A photograph of the forklift is presented in Figure 3. Although the original forklift has many of its functions electrically controlled, mechanisms with electrical servo motors had to be designed and built for steering and braking. The computation required for automated functionality is performed on four networked quad-core laptop computers, three on them located on top of the machine. [105]

Figure 3. Proof-of-concept of an automated forklift. [105]

A GNSS receiver with an integrated IMU is included and wheel encoders are installed into the front wheels. A sensor with CAN interface is added for measuring the tilt angle of the fork. Encoders are used to measure the height and lateral position of the fork. A total of 15 scanning lidars are used to measure objects around the forklift. Six of them are mounted low, angled 5° downward, one facing forward under the chassis. Five lidars are located on top of the forklift, scanning more steeply downward. Two of the lidars are installed on the fork for pallet detection, and another two scanning vertically forward on the sides of the forklift. [105]

Four beamforming microphones are used to detect shouted warnings. Four cameras are used to form a 360° view around the forklift for a remote operator. Speakers, a skirt of light-emitting diodes (LED) and LED matrix displays are added to signal to humans whether the system has detected them, and what actions the forklift is about to perform. Many of the lidars and LEDs are visible in

Figure 3. Each sensor is connected directly to one of the four laptop computers. A fifth laptop computer is used as a diagnostics display for the local operator. A wireless access point (AP) provides remote access. A PLC monitors heartbeat signals from higher level software run on the laptop computers and performs low-level control. [105]

1.3.3 Electronic control systems in automated mining

Marshall et al. have developed a system for automated hauling with an underground mining vehicle with articulated-frame steering (AFS). The system was tested with two machines originally built for manual operation. Both have a modular control system that is distributed over CAN. The system consists of ruggedized operator panels, display modules, I/O modules and proprietary computational modules that tolerate the demanding mining environment. The computational modules have a real-time operating system. [76]

To enable automated functionality, the machines were equipped with extra sensors and embedded computers. On one of the machines, an Intel Pentium III–based computer operating at 700 MHz, was added. On the other one, an Intel Pentium M–based computer at 1.5 GHz was used. On both machines, two horizontally scanning lidars were installed: one for each travel direction. The lidars have RS-485 interface, which is not available in either of the embedded computers. RS-485-Universal-Serial-Bus (USB) adapters are therefore used. The AFS angle is measured with an encoder that has a CANopen interface. Another encoder consisting of a toothed wheel and inductive sensors is mounted on the drive shaft. One of the machines with the extra sensors is presented in Figure 4. [76]

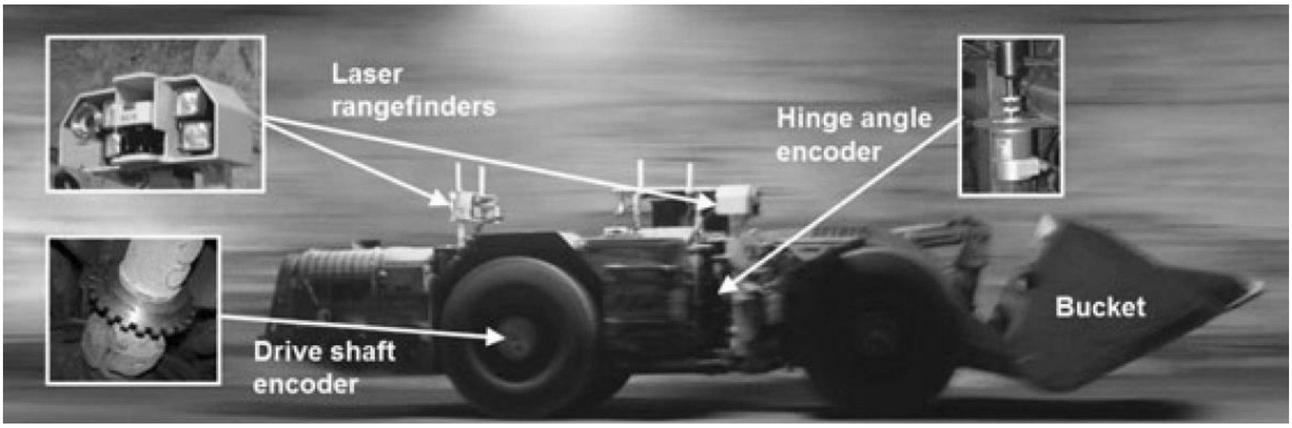

Figure 4. An automated mining machine with additional sensors. [76]

1.3.4 Electronic control systems in automated agriculture

Automated functions in agricultural applications are a common research topic. Commercial systems for farm tractors are also available. Recent research has aimed at improving the performance of automated steering when the tractor is towing an implement that affects the yaw dynamics of the tractor. Derrick developed adaptive algorithms for automated steering control. The algorithms were tested with a farm tractor which has hydraulic power steering. The steering valve can be commanded over CAN. Furthermore, the tractor has a differential GNSS receiver that is designed for agricultural use, supplied by the tractor manufacturer. In addition, automotive inertial sensors are installed to measure yaw rate and a linear potentiometer is installed to measure steering angle. [25]

An embedded computer with PC/104-based modular hardware and a QNX real-time operating system is used for implementing the controllers in real time. The computer has two expansion boards: one for CAN communication with the steering valve, the other for measuring analogue signals from the IMUs and the linear potentiometer. The embedded computer is located in an enclosure that protects against mechanical shocks and vibration. The GNSS receiver is connected to the computer with a V.24/V.28 serial link. [25]

The CAN-based communication between a tractor and an implement is specified in a well-established standard ISO 11783. Backman studied how a decentralized and generic combined navigation system of a tractor and an implement can be realized using standardized communication. A system for combined navigation was developed and tested. The hardware architecture of the navigation system is presented in Figure 5. A combined seed drill was used as an implement. The system was tested in two field tests with two different tractors towing the seed drill. Both tractors accept steering curvature commands according to ISO 11783, and one of them also supports speed control. [10]

The drawbar of the seed drill is modified by adding an articulated joint that can be hydraulically steered. The steering cylinder is controlled by an auxiliary valve of the tractor. An inductive non-contact sensor has been added to measure the angle of the controlled joint. An angular potentiometer is used to measure the freely moving joint between the tractor and the seed drill. The signals of these sensors are transmitted to the ISO 11783 network. A measurement system is installed on the roof of the tractor for pose estimation. It consists of an RTK-GNSS receiver with Virtual Reference Station (VRS) service, an IMU, optionally a separate fibre optic gyroscope, and a microcontroller board that merges the data and transmits it over the ISO 11783 network using NMEA 2000–compliant messages as specified by National Marine Electronics Association. The GNSS receiver and the sensors have V.24/V.28-based serial communication with the microcontroller. In addition, the wheel encoders and the ground speed radar of the tractor are used for pose estimation. [10]

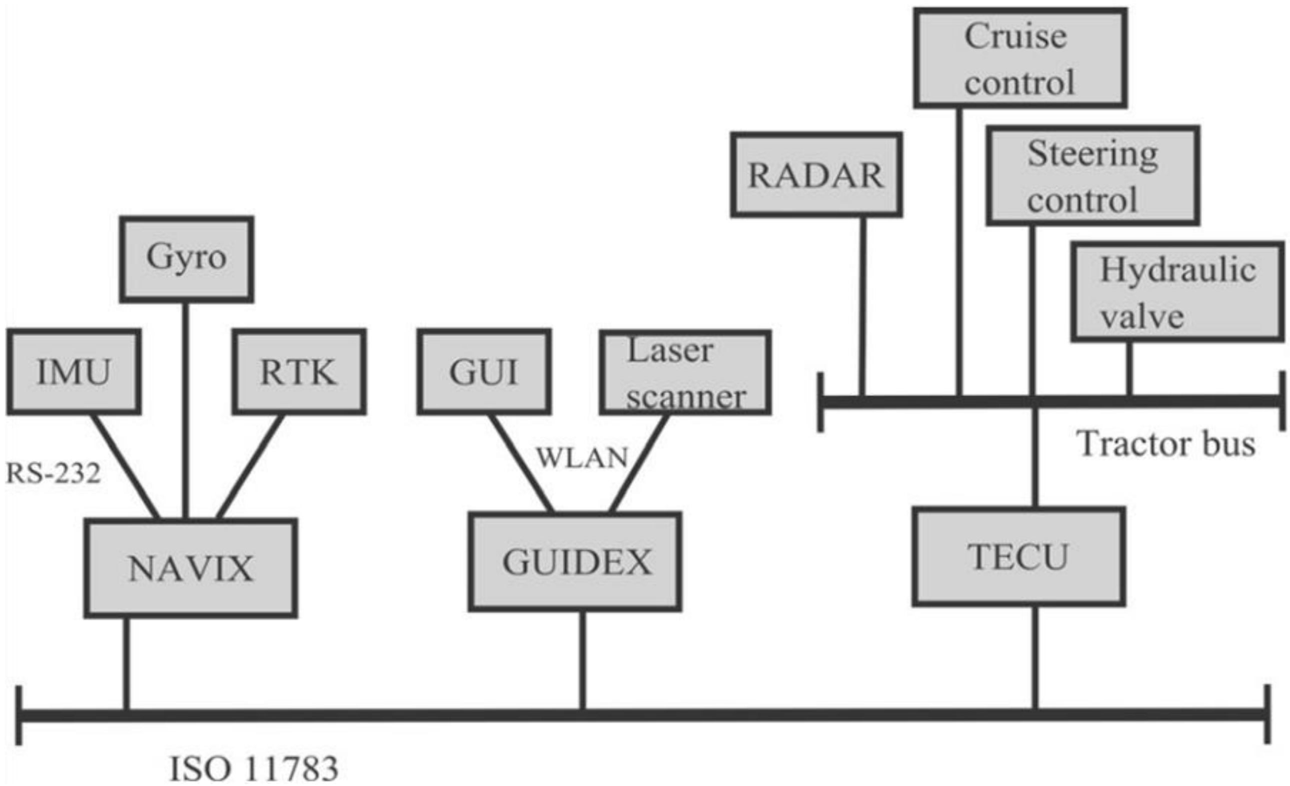

Figure 5. Hardware architecture of tractor-implement navigation system. [10]

A vertically downwards scanning lidar is installed on the seed drill to detect the adjacent swathe left in the field by the previous drive. A similar lidar, installed horizontally scanning, is mounted in front of the tractor for obstacle detection. The lidars are equipped with IEEE 802.11–based wireless interface. The computing of the guidance system is performed by an Intel Core 2 Duo–based desktop computer with a CAN-USB adapter and an IEEE 802.11 wireless interface. Although the communication between the tractor and the implement can be realized over ISO 11783, some proprietary messages are required. Backman proposes ISO 11783 to be updated to define the communication in these cases. [10]

1.3.5 Electronic control systems of automated off-road vehicles

Green has researched path planning for automated off-road vehicles in unstructured environments. The algorithms are tested with a rugged amphibious vehicle, although the tests are performed only on land. The skid-steered vehicle has eight wheels driven by a petrol engine, a variable ratio torque converter and a manual gearbox with differential. The skid-steering is realized with separate hydraulic brakes for both sides. An electronic control system for automated operation is retrofitted on the commercial vehicle. An extra alternator and a deep-cycle-tolerant 24 V battery system were installed because the original 12 V system does not supply sufficient electrical power for the retrofitted control system, especially when operating the engine at low speeds. [42]

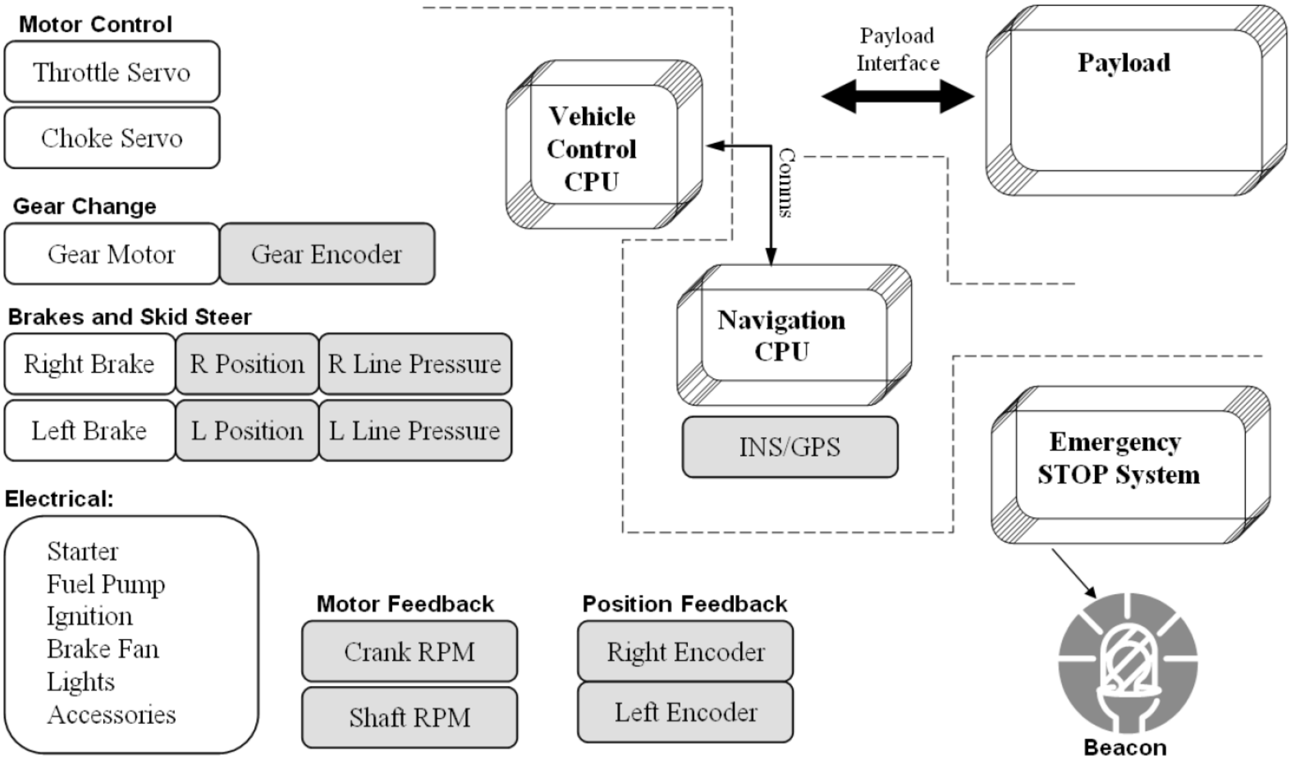

Figure 6. Hardware architecture of retrofitted control system for off-road vehicle. [42]

The hardware architecture of the retrofitted system is presented in Figure 6. The sensors have a grey and actuators a white background in Figure 6. The angular velocities of the engine, torque converter output and wheels on both sides are measured with encoders. Sensors for measuring position and pressure of each brake actuator are installed, as well as limit switches. Limit switches are also mounted on the gear selection mechanism. A GNSS receiver with an integrated IMU is used for global pose estimation. Electrical servo motors and controllers are used for throttle and choke control. The electrical actuation of brakes and gear selection are not described. There is one computer for navigation and another for low-level vehicle control. The vehicle control computer has an expansion board for analogue I/O. The sensors and actuators are connected to the expansion board, apart from the electrical servo controllers that communicate with the computer via a V.24/V.28 serial link. There is also an emergency stop system that can override the actuator control signals from the vehicle control computer with a separate hardware signal. The computers are connected with Ethernet, CAN and a V.24/V.28 serial link. In addition to the retrofitted system, extra sensor, actuator and computing modules can be installed. The modules need to tolerate the power supply from the 24 V system, have CAN or Ethernet communication and support the emergency stop functionality when applicable. To map the terrain for path planning tests, Green uses a module that consists of three horizontally scanning lidars. [42]

Kelly et al. research the performance of an autonomous vehicle in different challenging test environments. Two generations of automated off-road vehicles are developed. The vehicles are based on human-operated all-terrain vehicles that are modified to be electrically controlled. The second generation of vehicles included an auxiliary generator for supplying the sensors and computers. Pose estimation is performed based on encoders measuring steering angle and angular velocity of the engine, a differential RTK-GNSS receiver, ground speed radar, linear potentiometer measuring suspension travel and an IMU. The perception system consists of several single-plane lidars, two stereo camera systems and several separate cameras, some of them thermal. In addition, the vehicle has a pressure-sensitive bumper. Some of the lidars are rotated by an electric motor. With slip rings for power and communication, they are able to rotate continuously. One of the rotated lidars is mounted on a controlled mast, enabling negative obstacles to be detected from a distance. In addition to the colour and thermal cameras used for terrain classification, there are several cameras for direct teleoperation. The vehicles are able to supplement on-board sensing by launching an automated helicopter and receiving aerial lidar and camera data. A second generation vehicle with sensors and antennas is shown in Figure 7. [66]

The computing system consists of several Intel Pentium or compatible computers, each with a dedicated purpose: sensor and wireless interface (excluding stereo and teleoperation cameras), planning and hardware-accelerated stereo camera processing, teleoperation camera interface, top camera and lidar processing, and low-level sensor interface with actuator control. All the computers are clocked at 1–2.4 GHz and communicate over Ethernet at 1 Gb/s (1000BASE-T). A separate pulse-per-second (PPS) signal is connected to all the computers. The signal causes an interrupt that is used to synchronize the real-time clocks of the computers, which enables precise pose tagging and fusion of sensor data. [66]

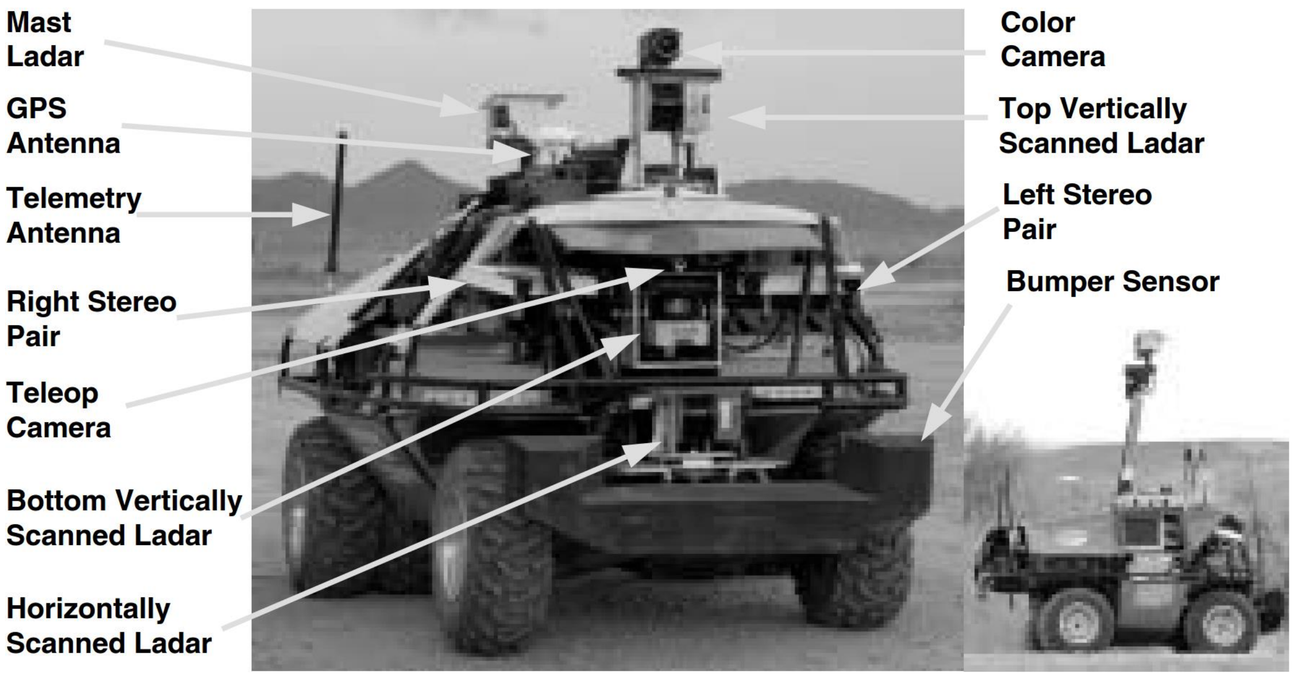

Figure 7. Sensor and antenna locations on automated off-road vehicle. [66]

1.3.6 Automated excavation

Various research projects have been targeted at automated excavation and several arrangements have been patented. Caywood et al. filed an application as early as 1965, describing a hydraulic-mechanical solution. [18]

Singh has conducted surveys on research over the recent decades. Singh discusses the development of automation in earthmoving considering sensing, modelling, planning and control. The focus in sensing is mainly on lidars. Actuator and soil-tool interface modelling are discussed. Dig and dump planning are considered. Free-space motion control as well as digging control is covered. [102]

Hemami and Hassani have prepared an overview of autonomous loading. A typical truck loading scenario is considered and the functional requirements are listed. Although navigation and obstacle avoidance are mentioned, the main focus is on excavation. The challenges related to soil-tool interface are debated and relevant previous research is summarized. [48]

Cannon describes an automated excavator that is developed for truck loading. The excavator is able to observe the shape of the surrounding soil to decide where to dig. Furthermore, the trucks to be loaded are detected and the dump position on a truck is automatically chosen. The excavator is able to move in case the dig and dump locations are different. The excavator reaches roughly the operating speed of an expert human operator. Although human assistance is needed, the excavator may operate several hours independently. The original machine is modified to support electrical control of the hydraulic system. Therefore, the swing, boom, stick, bucket and track movements are controlled by the electronic control system. Angular resolver sensors are mounted at each joint. Pressure sensors are installed to measure the actuator force of each hydraulic actuator. Perception is performed by two scanning lidars mounted on the roof of the excavator. There are controlled platforms that are used to point the lidars. The computer for automated functions consists of an array of four processors. Cannon has the main focus on dig planning. The developed planner is a perception-based system that exploits models of excavator dynamics and soil-tool interaction. [15]

Ha et al. present an experimental automated excavator. A commercial small excavator is modified for electrohydraulic operation. According to Le et al., the machine has eight hydraulically controlled movements: tracks, cab swing, boom swing, boom, stick, bucket and backfill blade. Mechanically controlled valves have been replaced by electrohydraulic servo valves. Additional hydraulic components required by the servo valve are added. The servo valves are equipped with spool position sensors. Actuator pressure sensors are installed on the hydraulic system, and load pins on the excavator joints. Rotary absolute encoders are fitted to joints with timing belts. Encoder installations are protected by steel guards. Closed loop control of the actuators is performed by proprietary digital control modules. An industrial computer with a Windows NT operating system is installed on the machine for higher level control. Furthermore, the computer can be used to host a transputer network for parallel processing. The industrial computer communicates with the digital control modules over CAN. Two short-range lidars are used to scan the terrain on both sides of the bucket. The operator’s cab has been removed. The electrical system of the excavator is used to power the electronic control system. [44][68]

A digging controller with robust sliding mode control and a task planner with hierarchical-behavioural approach are developed. Experiments with loading and trenching are performed with the excavator. The results are close to the performance of human operators, especially when the soil is not very hard. [44]

Maeda et al. have used the same excavator to experiment with iterative trenching, without utilizing a model of the soil-tool interface or actuator force measurements. Cartesian impedance control is applied. The reference trajectories are generated based on a penetrate-drag strategy. Feedforward actions are pre-calculated using the free-motion inverse dynamics of the boom, stick and bucket. A variable structure observer is implemented for disturbance compensation. The results are presented with and without disturbance compensation. It is concluded that the proposed iterative control will converge towards the reference trajectory in more demanding conditions if disturbance compensation is applied. [75]

1.3.7 DARPA challenges

Several automated off-road vehicles with path-following and obstacle avoidance capabilities have been developed for the Grand Challenges organized by the Defense Advanced Research Projects Agency. Later, the focus has been on automated driving with other traffic and pedestrians present in the DARPA Urban Challenge. Although most of these vehicles cannot be considered experimental mobile machines, there are similarities in the design objectives of the control systems: demanding environmental conditions, sensor types and on-board communication can be close to automated mobile machinery. Moreover, the research and development work in these projects may be done by dozens of people at different locations, and further work may continue over a decade with the same vehicle platform. Therefore, modular and flexible hardware and software solutions are often desirable in these projects.

Braid et al. developed the control system for an automated off-road military truck, TerraMax. The truck has six wheels, all-wheel drive and all-wheel steering. The computers and networking equipment are installed in a suspended rack under the passenger seat. A display, keyboard and mouse for on-board testing and development are mounted on the dashboard of the truck. The sensors are fixed to the roll cage with adjustable mounts that tolerate shocks and vibration. A cleaning system is installed to enable automatic washing and drying of the sensor lenses. An electrically actuated proportional pressure control valve is used to control the brakes. The throttle is controlled by generating a pulse-width-modulated (PWM) voltage signal for the original engine control unit. Gear selection is already electrically actuated in the original truck. An electrical servo motor is mounted in parallel with the steering wheel. The original truck has a dual-input steering gearbox which makes parallel installation straightforward. [12]

The hardware architecture of the control system is presented in Figure 8. The system is distributed over Ethernet at 100 Mb/s (100BASE-TX). A conventional internet protocol suite is used. Computing is distributed over several embedded computers. One of the computers has an I/O expansion board for gearbox and throttle control. Two differential GNSS receivers with integrated IMUs are used in pose estimation for redundancy. A wheel odometry signal is connected to the GNSS units to improve read-reckoning performance during poor satellite reception. One of them is configured to perform differential calculation with a satellite-based augmentation system (SBAS); the other receives differential corrections via a V.24/V.28 serial link from a third, agricultural GNSS receiver with a subscribed OmniStar correction service. Obstacle detection is performed by three cameras and four scanning lidars: two single-plane and two quad-plane models. Only one of the quad-plane lidars is used at a time, the other is for backup. The single-plane lidars communicate over V.24/V.28 serial link; the quad-plane models have external electronic control units with Ethernet interface. The cameras have an IEEE 1394 interface and they are arranged into a trinocular vision system. [12]

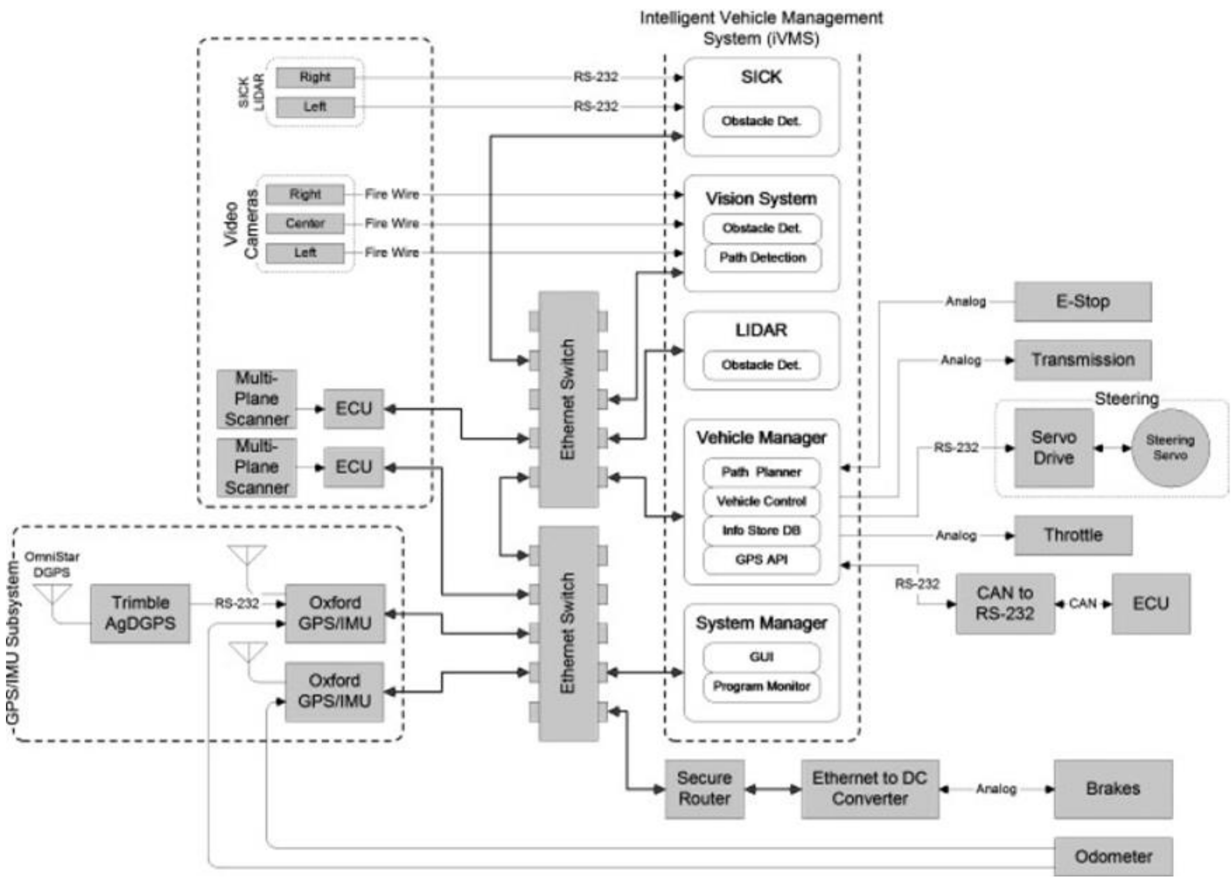

Figure 8. Hardware architecture of control system of TerraMax. [12]

Urmson et al. present the development of two automated military vehicles: Sandstorm and H1ghlander. In addition to embedded computers, the control systems include several embedded modules of one or more microcontrollers that run a real-time operating system each. The modules are connected with automotive grade data links. Hardware-related functions are developed in C and assembler but MATLAB/Simulink with automated code generation is used to implement control routines. The original alternators of the vehicles are removed. Because the maximum power consumption of the electrical system also exceeds the ratings of the replacement generators, both vehicles have microcontroller modules controlling the generators and the voltage converters based on loading conditions. There is a separate radio link for remote emergency stop. [116]

Sandstorm is customised exclusively for automated operation: the roof and passenger compartment are removed. Sensors and computers are installed on a suspended platform for protection. The movement of the suspended platform in relation to the vehicle frame is not measured, which affects path-following performance, for example. A separate small diesel engine and a 24 V generator are installed to supply electrical power instead of the original alternator of the vehicle. Heat management of the electronics is realized by installing an extra evaporator inside the electronics cabinet. The compressor of the cooling system is driven by the main engine. A large gearwheel is mounted behind the steering wheel for electrically actuated steering. The gearwheel is paired with an electric motor. The actual steering angle is measured by a sensor at the output of the power steering gearbox. A multi-turn angular sensor is included in the electric motor for redundancy. A microcontroller module performs close loop control of the steering angle. Since the original engine has a mechanically controlled injection pump, an automotive throttle actuator is modified and fitted on the engine. The actuator consists of an electric motor with an integrated position sensor. A microcontroller module is used to control the actuator angle. The brake pedal is actuated by an electric motor with a reduction gear. Torque-based control is realized with a microcontroller module. [116]

The electrical system of the H1hglander is replaced by the system of a later model of the same vehicle to make transmission and engine control accessible in the software. Although a suspended enclosure is installed for the embedded computers, the sensors of the H1ghlander are mounted without extra suspension. A 340 V switch-reluctance generator supplies an electric air conditioning compressor and step-down voltage converters for 24 V and 12 V devices. The original steering system has been replaced by an electro-hydraulic system: A hydraulic rotary actuator is controlled by an electrically actuated proportional valve with integrated closed-loop spool position controller. The hydraulic power is generated by a fixed-displacement pump. A rotary sensor is mounted on the shaft of the rotary actuator. The position of one of the cylinders of the rotary actuator is measured for redundancy. A microcontroller module performs closed-loop control of the steering angle. The engine control unit of the updated electrical system has CAN communication. The brake master cylinder is actuated by an electric motor with a reduction gear. A microcontroller module performs torque-based close-loop control. [85][116]

The perception and computing system is similar in both vehicles: one horizontally scanning long-range lidar is mounted on an actively controlled gimbal. This is done because the pitch and roll angles of an off-road vehicle change rapidly during drive and cause distorted range measurements. In addition to stabilizing the lidar, the active control makes it possible to point the lidar at different areas of interest. The stabilized lidar is used with two short-range lidars for terrain characterization. Another two short-range lidars are used for detecting positive obstacles. To improve perception performance through dust, a horizontally scanning radar is also installed. A dual-antenna GNSS receiver with an integrated IMU and data fusion is used for pose estimation. The pose estimation algorithm also uses odometry data. A camera with IEEE 1394 interface is installed for documentation. The computing is distributed over Ethernet (1000BASE-T) between 11 computers. Seven of them are built of modular CompactPCI hardware with Pentium M processors. The remaining four consist of modular PC/104 hardware based on Pentium III processors. All the computers have an operating system based on Fedora Linux kernel and communicate over the internet protocol suite. The communication with microcontroller modules that control steering and velocity is realized with CAN. The hardware architecture is presented in Figure 9. [85][116][125]

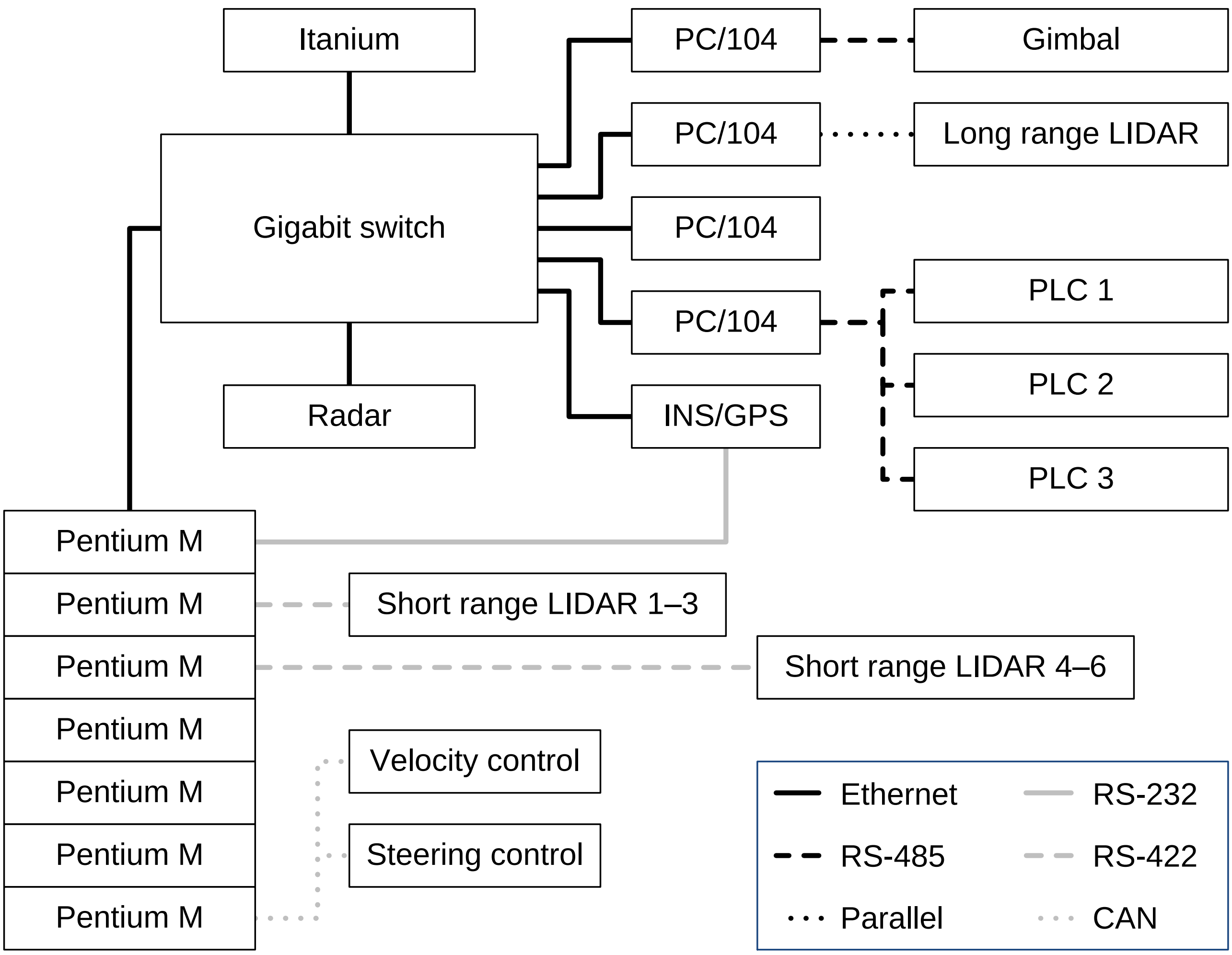

Figure 9. Hardware architecture of Sandstorm, adapted from [125].

In 2007, DARPA organized the Urban Challenge which is the most recent DARPA competition where hardware architectures of control systems were developed for autonomous vehicles. The most obvious update in control system hardware compared to the Grand Challenges is probably in the perception equipment for detecting other vehicles, pedestrians, road markings, etc. The sensors are generally the same as in the Grand Challenges, but there are more of them. As a result, more software development and higher computing performance are required. Furthermore, all the networking and hardware architectures of the Grand Challenge vehicles are not flexible enough for adding this new equipment.

Leonard et al. equipped a vehicle with a perception system of 12 single-plane lidars, 15 automotive radars, 5 cameras and a 64-plane lidar. The aim was that all sensors communicate over Ethernet, preferably with user datagram protocol (UDP) multicast to minimize network load. Unfortunately, most of the sensors do not have an Ethernet interface. A serial server is used to collect the serial data from the single-plane lidars and transmit it over Ethernet using the internet protocol suite. The radars have a fixed automotive firmware and each requires a dedicated CAN. Several adapters are used to interface these 15 CANs into Ethernet. The cameras are connected to a computer that transmits compressed image data over Ethernet to other computers. The computing is realized with a modular blade server system. Considering the overall power consumption of the control system, there is no suitable alternator with sufficient power rating. Therefore, a separate engine-generator unit and uninterruptible power supplies (UPS) are used. [72]

Urmson et al. developed a perception system with six single-plane lidars, a 64-plane lidar, two automotive lidars, two quad-plane lidars, five automotive radars and two cameras with a high dynamic range. Most of the sensors have a fixed mounting. Some of the lidars are pointed down for detecting lane markings, as road paint is generally more reflective than road surface. An automotive lidar and radar are mounted on a controlled pod on both sides of the vehicle. A differential GNSS receiver with integrated IMU, wheel odometry input and data fusion is installed for coarse pose estimation. Devices for low-level actuator control are supplied by the original 12 V system of the vehicle. For sensors and computing, an auxiliary 24 V alternator, battery pack and several voltage converters with power management functionality are installed. An interface for external power supply is included. Circuit protection and power distribution are arranged to ensure that no single protective device opening its circuit will produce a complete gap in the coverage area of the perception system. The original cooling system of the vehicle is used for thermal control. Computing is performed by ten Core2Duo-based computers at 2.16 Ghz with 2 GB of random access memory (RAM), a 4 GB flash drive and a dual Ethernet interface supporting 1000BASE-T. Two 500 GB hard disk drives are included for data logging. The computers are CompactPCI modules installed in a common chassis. The computers are synchronized with a customized PPS adaptor board and communicate using the internet protocol suite. [117][118]

1.3.8 Summary

The publications presented above describe several electronic control systems of automated machines and vehicles. The level of automation ranges from automated steering to machines capable of operating independently several hours. A typical system has lidars and cameras for perception, a GNSS receiver and an IMU for pose estimation and several computers. These devices typically communicate over Ethernet, and interface with low-level controllers via CAN and V.24/V.28 serial communication. The reasons for choosing the data transfer solutions and hardware architectures are typically not discussed in detail.

The life-cycle manageability of the presented control systems of automated mobile machinery is not discussed in literature. The presented research on life-cycle manageability, on the other hand, is focused on control systems with conventional I/O and does not cover the sensors and computers required in automated mobile machinery.

1.4 Research questions

The aim of this thesis is to find out how the electronic hardware of the control systems of future automated mobile machinery has to be designed. This objective is formulated into the following research questions:

What are the limitations of applying different communication technologies?

There are different communication technologies that may be applied to a control system. What are the limits in network throughput and segment length? What are the differences in deterministic communication delay, cost-efficiency, and electrical and mechanical robustness? Which technologies are feasible in respect of life-cycle manageability?

What are the essential device-related design aspects concerning sensing, actuation, computing and electrical power supply in contrast to designing manually operated machinery?

Utilizing state-of-the-art sensors and computers in mobile machine applications is not straightforward. How to realize the electrical power supply for devices that cannot be supplied directly from the battery system of a mobile machine? Which device types require extra protection against environmental conditions? Which communication technologies to utilize when communicating with different device types, taking life-cycle manageability into account?

How to interface devices that cannot be connected directly to mobile PLCs or I/O modules?

Research and development projects involve interfacing new devices into existing control systems. These devices have interfaces that are not present in the control system at all, or not in a sensible location regarding the architecture of the control system. In addition, utilizing these devices may require harder real-time calculation than possible in the control system. How to interface a device like this into the control system of a mobile machine? How to minimize the prototyping work when utilizing customised microcontroller-based devices as interfaces?

1.5 Scientific contribution

The scientific contribution of this thesis in relation to previously conducted research on mobile machinery is presented in Figure 10. The previous research on life-cycle manageability of control systems is partially applicable to automated mobile machinery but does not cover the extra sensors and computers required for automated operation. The published research on automated mobile machines, on the other hand, is concentrated on describing the performance of the developed automated functionality. Although hardware architectures or lists of utilized devices are published, the development process of the hardware architecture of the control system is not discussed in detail. Life-cycle manageability, in particular, is not discussed, probably since the developed systems are not intended for long-term operation.

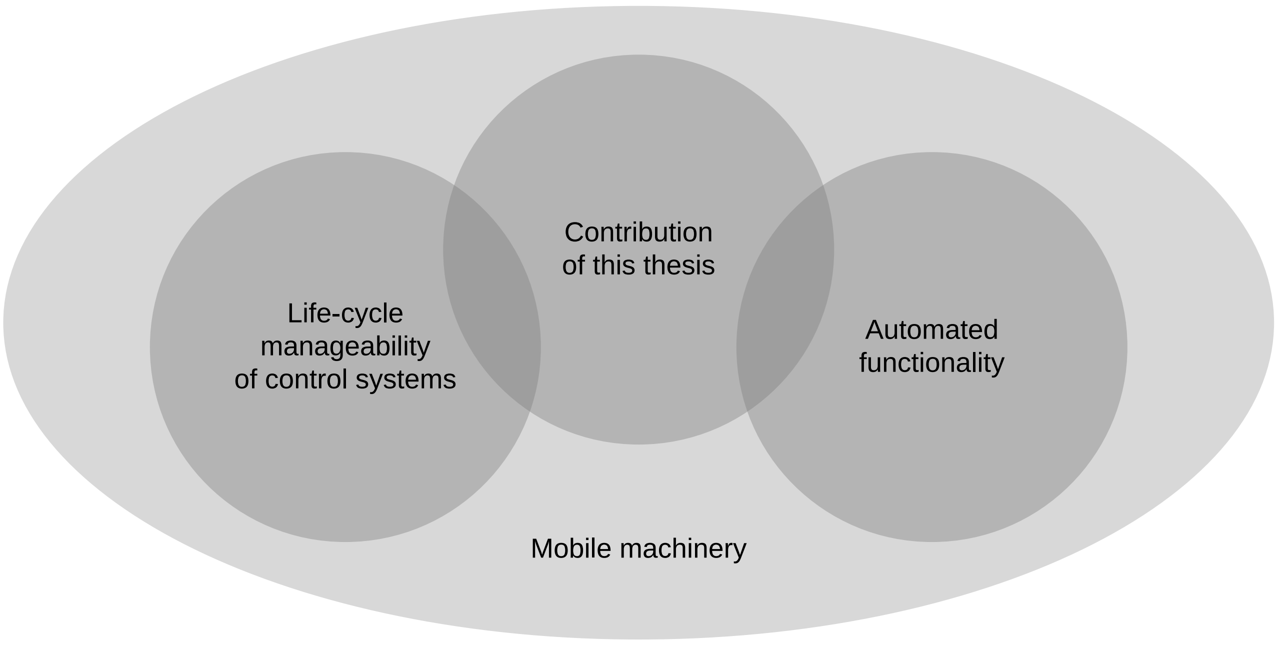

Figure 10. Contribution of this thesis in relation to previous research.

The scientific contribution of this thesis is the following:

Feasibility assessment of different digital networks and buses for automated mobile machinery

The feasibility assessment is done in Chapter 3. The key characteristics are compared in Table 2 and a proposed arrangement to utilize different data transfer solutions is presented in Figure 13.

Compilation of hardware-specific challenges and design aspects in the electronic control systems of automated mobile machinery

The challenges and design aspects are discussed in Chapter 4. In particular, a proposed workflow for specifying the voltage of a battery system is presented in Figure 15 and a proposed reference hardware architecture of an automated mobile machine is presented in Figure 20.

Design of a generic embedded module for interfacing prototype devices with a distributed control system

The design process of the embedded module is presented in Chapter 5. In addition to designing and implementing the embedded module, applying the module on devices presented in Chapter 6 and Chapter 7 are contribution of the author, apart from developing the real-time algorithm for wheel odometry.

Demonstration of the above contributions in two experimental automated machines

Designing and implementing the control systems presented in Chapter 6 and Chapter 7 are partial contribution of the author. The excavator control module, in particular, and its control software demonstrated in Chapter 7 are developed and experiments conducted by the author. Comparison of the control systems with the proposed reference hardware architecture is presented in the end of Chapter 6 and Chapter 7.

1.6 Outline of thesis

In Chapter 2, the requirements for control systems of automated mobile machinery are presented. The characteristics of mobile machinery, the required sensor and actuator interfaces, communication, and properties of multi-machine environments are discussed.

The feasibility of different solutions for data transfer is discussed in Chapter 3. These include the typical buses and networks an automated machine has on-board.

In Chapter 4, the challenges linked to different types of devices required in automated machinery are discussed. Devices for embedded computing, pose estimation and perception are included.

A generic microcontroller module that can be used to interface new sensors and actuators with the control system is presented in Chapter 5. The design criteria, features and construction of the module and application-specific use are presented.

In Chapter 6, a wheel loader with automated path following is presented as an example. The control system architecture and individual devices are described. Meeting the requirements for control systems of automated mobile machinery is discussed.

The control system of a small remotely operated skid steered wheel loader with an automated excavator is discussed as another example in Chapter 7. The architecture of the control system hardware is presented. The implementation of operator-assisting functionality is described and test results are shown.

Finally, conclusions are drawn. Guidelines for designing the control systems of automated mobile machinery are proposed.

2 Application-related requirements for electronic control systems

Automated mobile machinery has special requirements for electronic control systems that pose design challenges. In this chapter, these requirements are presented. The requirements are divided into ones that derive from long life cycles and demanding operating conditions of mobile machines, ones that are related to automated functions and ones that are specific to multi-machine environments.

2.1 Mobile machinery

Mobile machines have longer life cycles than electronic components. Therefore, a machine is likely to have its electronic control system at least partially updated or upgraded at some point. In addition to changing spare parts, new functionality is added to old machines. To reduce the costs of these changes, the control system has to consist of generic modules that are straightforward to replace. The spare part stock can be kept smaller if one generic module can be configured to perform different tasks. The architecture of the control system also has to be flexible so that the control system can be extended by adding new devices.

Mobile machines often operate in demanding conditions: extreme temperatures, dust, snow and high-pressure water are not uncommon. Not only do the machines work on rough terrain but heavy vibration and shocks are also generated by the on-board mechanisms and engine. Although some sensitive devices may be located inside a cabin, in general, dust and water proof enclosures, robust construction and thermal management are required. The electrical devices that are neither cleaned with a pressure washer nor sunk into water still require a minimum degree of protection of IP55 as specified in IEC 60529 [23]. The devices need to operate over an ambient temperature range of −20 °C to 50 °C, at minimum. For devices mounted next to an engine or exposed to direct sunlight this is not sufficient. In addition, single electronic components inside an enclosure may need to operate at up to 125 °C due to the heat generated inside the enclosure. On the other hand, extreme winter applications may require operating temperatures as low as −40 °C.

Mobile machines are used for diverse tasks. Excavators and wheel loaders, for example, have several optional tool attachments. Machines are operated in closed environments but also driven in public traffic. The control system must not limit this flexibility, even if automated functionality is added. If a machine is designed to be fully automated or remotely operated, the operator's seat and cabin can be left out. However, the option to drive or operate an automated machine manually from the operator's seat is often desired. This is the case, for example, if a machine is driven on public roads between closed working sites, or automated functionality is forbidden on some sites. Manual driving may also be needed for maintenance.

2.2 Automated functions and remote operation

Manually operated machines have diesel engines, working hydraulics, and steering and braking systems that can be used to implement automated functionality. They also have several sensors that can be used. All requirements for actuators, sensors and data transfer are, however, usually not met in manually operated machines.

2.2.1 Requirements for actuation and sensing

To enable remote and automated control, an automated machine needs to have electrically controlled functionality. Depending on which functions are automated, some functionality may remain mechanically or hydraulically controlled. For example, automated driving requires electrically controlled acceleration, braking, steering and gear selection, but working actions may still have mechanical control levers.

Automated functionality often requires sensors that are not present in manually operated machines. Measured quantities are, for example, the positions of work mechanisms, hydraulic load pressures and centre link angle in an AFS machine. In some applications limit switches are sufficient, but usually actual sensors are needed. For automated drive, the angular velocities of wheels, global position and orientation of the machine and inertial signals typically need to be measured. Depending on the level of automation, also different types of cameras, radars, lidars or ultrasonic sensors are required.

2.2.2 Requirements for on-board data transfer

The control system of an automated machine implements several closed-loop controllers, which increases the number and transmission rate of sensor signals compared to a manually operated machine. In addition, sensors with high output data rate are utilized. Approximated payload data rates of different device types are listed in Table 1. Devices that do not involve cyclic data transfer are omitted.

Table 1. Data rates of device types.

Device	Size of one measurement cycle	Rate [Hz]	Data rate
Diesel engine, target rotation speed	12 b	50	600 b/s
Proportional valve, target spool position	16 b	50	800 b/s
GNSS receiver, RTK latitude & longitude	96 b	10	960 b/s
Joystick, 3 axes	30 b	50	1.5 kb/s
Wheel odometry, single wheel	16 b	100	1.6 kb/s
Linear or angular position sensor	16 b	200	3.2 kb/s
Pressure sensor	10 b	500	5 kb/s
IMU, 6 degrees of freedom	96 b	200	19.2 kb/s
Monitoring camera, 320 by 240 pixels, H.264 compression [5]	–	10	192 kb/s
Single-plane lidar, 270° scan at 0.25° interval, distance only	17.3 kb	25	432 kb/s
Machine vision camera, 1920 by 1080 pixels, 8-bit Bayer pattern	16.6 Mb	10	166 Mb/s

In this thesis, a typical control system of an automated mobile machine is assumed to have ten pressure sensors, six proportional valves, two joysticks, and six linear or angular sensors. Uncompressed digital video and two lidars are utilized for perception while compressed video is transmitted for direct teleoperation. A GNSS receiver, an IMU, and wheel odometry of four wheels are used in pose estimation. The data transfer of these devices, including overhead, must not cause more than 50 % network load on-board, leaving bandwidth for distributed computation and devices to be added in further development.

2.2.3 Requirements for wireless data transfer

Remotely operated mobile machines need wireless data transfer to receive control signals from the remote operator. This is clear in the case of direct teleoperation as described by Sheridan [101]. However, even machines with a high level of autonomy communicate with a supervisor, exchanging mission or task information. The requirements for wireless data transfer depend heavily on the application.

In direct teleoperation control signals are transmitted in real time. Therefore, the delay of wireless communication has to be minimal. In this thesis, the maximum acceptable delay including the transmission of a control command and reception of a visual feedback is 100 ms. If a video stream is not transmitted from the machine to the operator, the required data rate of the wireless communication is low. This can be the case if the operator is able to see the machine directly or the working site has a low-latency camera system for direct teleoperation. A wheel loader, for example, can be operated with four 5-bit control values transmitted every 100 ms, requiring simplex communication with a throughput of 200 b/s. It is also possible that instead of a real-time video stream, the machine transmits sensor data, and the machine and its environment are visualised to the operator with computer-generated graphics. It is, however, often safer and more convenient to use on-board cameras. The minimum acceptable video quality in this thesis is considered to be 320 by 240 pixels at 10 frames per second. Utilizing H.264-compliant video compression, a video stream of the minimum quality has a data rate of 192 kb/s maximum. [5] In direct teleoperation, lost data does not need to be retransmitted when new data is available. This applies to both control signals and video stream.

Depending on the level of autonomy, an automated machine may require a new subtask from the operator or external control system every second or a new mission every week. In any case, more delays in communication can be tolerated than when the machine is remotely operated. Lost data has to be retransmitted as transmission is usually not a continuous stream. However, if the automated machine transmits video or other sensor data for real-time supervision, the requirements regarding retransmission, delay and data rate are similar to direct teleoperation.

In this thesis, the control system must enable direct teleoperation over a wireless connection meeting the minimum specification above. In addition, task data is transmitted. The wireless technology has to have sufficient data rate for video transfer at the minimum quality described above. Wireless APs may be installed in the working area if required by the chosen wireless technology.

2.3 Multi-machine environment

It is most straightforward to implement automated machines that operate alone in a closed environment. There are, however, applications that require other machines, automated or manual, to be operated in the same area. The presence of other machines sets new requirements and restrictions for the control system of an automated machine.

On-site wireless communication may be intensive even without automated machinery. It is likely that one communication channel has to be shared between the machines. Therefore, the available data rate of wireless communication is divided. Moreover, with communication protocols, the overall ratio between payload and overhead data gets worse as the number of transceivers is increased. A common communication channel is also required if the machines have to communicate directly with each other.

A fleet of automated machines may perform coordinated tasks or missions. For this, an automated machine has to have wireless communication and embedded computing that are compatible with the fleet management system. This compatibility may, for example, require an on-board embedded computer to have a specific operating system.

When a single automated machine operates in a closed environment with no dynamic obstacles, collision prevention is straightforward to implement. In a multi-machine environment, however, the situation is more difficult. One solution is that all the machines receive subtasks from a fleet management system that makes sure no two machines go too near each other. When machines perform longer tasks automatically, this is no longer feasible. Instead, the machines need to communicate their position to other nearby machines and adapt their operation accordingly. This means that also manually operated machines need to have positioning and communication equipment. Working sites also have dynamic obstacles like manually operated machines without positioning equipment or unmapped objects moved by manual machines. In this case the automated machines need to have sensors to detect these obstacles.

In this thesis, the minimum requirement is that two automated machines may be operated in a closed environment simultaneously. There is no need to detect other machines or obstacles by on-board sensors. However, the hardware architecture of the control system must enable perception sensors to be installed later.

3 Feasibility of typical data transfer solutions

There are several ways to transfer measurement and control signals in hydraulic mobile machines. Keeping the control system architecture modular, robust and generic can prove difficult even with manually operated machines. The problem becomes more complex when the functions of a machine are automated and it is operating in a multi-machine environment. This requires sensor and computation devices that have not been used in mobile machines before. Furthermore, as these devices are not targeted at mobile machine applications, they have limited compatibility with typical control system I/O, buses and networks.

In this chapter, the challenges related to these means of data transfer are discussed.

3.1 Non-digital interfaces

Most sensors first convert the measured quantity into an analogue electric signal, typically voltage. More advanced operations such as signal processing, amplification, conversion and digital interfaces may follow. Many sensors and actuators are available with an analogue or a digital interface. Because the analogue versions have lower pricing, digital versions are used in commercial systems only when the benefits are clear.

A digital interface is usually slower to develop than the analogue version. Therefore, when a new device is introduced onto the market, the version with analogue output is sometimes released first. Furthermore, some devices are targeted at completely analogue processing. Especially with high-frequency signals, digital processing may not be reasonable.

Unlike digital interfaces, an analogue signal does not include any information on the relation between the measured physical quantity and the electric signal. Therefore, gains and offsets need to be defined for all analogue signals. These may differ even between two similar devices from the same manufacturing batch. Regarding modularity, this is a key problem common to all analogue interfaces.

Interference is a common problem with analogue signals. In a mobile machine, the electric power supply is typically an alternator with a battery. The alternator is an AC generator with a rectifier. Therefore, the output voltage has a ripple with a frequency that is proportional to the rotation speed of the engine. The battery does not attenuate the alternator ripple completely but it remains a significant source of interference through both conducting and radiation. Other potential sources of ripple are switching mode converters. There are also inductive loads such as mobile hydraulic valves and electric motors that generate interference when they are switched.

A separate conductor is used for each analogue signal in a control system. This results in high cable costs and increases the probability of a cable or connector fault as the number of signals becomes higher. Each conductor is also a potential source of interference for the signals of the neighbouring conductors.

Analogue sensor signals are typically connected to an ADC of an I/O module or a mobile PLC. Depending on the properties of the analogue signal, there are several design considerations: amplification, anti-aliasing filter, ADC resolution, sampling frequency and digital signal processing. Similar parameters need to be decided when analogue actuator signals are produced by digital-to-analogue converters (DAC).

3.1.1 Continuous analogue signals

Voltage signals are the most difficult type of analogue signals regarding interference. Therefore, they only have to be carried over short distances in a mobile machine. Designing a cost-effective generic voltage input or output circuit is difficult due to several commonly used voltage ranges. Moreover, as mobile machine control systems mainly consist of single supply devices, the ranges that include negative voltage values are challenging to process.

Measuring a resistance includes transferring a voltage signal. Therefore, simple resistive sensors have the same problems as devices communicating by voltage signal. In addition, resistive sensors may require biasing or bridge circuits.

In general, current signals are more tolerant of interference. Most devices use an established current range of 4 to 20 mA. This makes a generic approach easier. Moreover, a sensor may operate with two conductors as no separate ground conductor is needed. Compared to voltage signals, this can reduce cabling substantially.

3.1.2 Pulse signals

Voltage pulses that carry signals in either frequency or pulse width are quite convenient in the sense of interference. They can be connected to conventional digital I/O. However, for high frequencies or accurate pulse widths a dedicated pulse I/O with hardware timer or counter, or both, is needed. Pulse signals are often transmitted by open-collector circuits. Therefore, external pull-up or pull-down resistors are required, depending on the circuit. Rating these resistors depends on the type of the output transistor, supply voltage, maximum pulse frequency and accuracy requirements. Moreover, mobile I/O modules typically have no convenient way of installing external resistors. This may result in the need for separate enclosures or connector blocks for resistors. Because of this, most pulse signal devices are not easily interchangeable. On the other hand, a single product may be configurable for several operating voltages.

A special case of pulse frequency signals are quadrature signals. A quadrature interface has two square wave signals that have −90° or 90° phase difference. These signals are typically used for calculating angular or linear movement: Each edge of either signal corresponds to a small change in rotation or displacement and the sign of phase difference indicates the direction of the change. Quadrature outputs are typically push-pull-type. Therefore, there is no need for external resistors. On the other hand, quadrature devices often operate at a fixed signal voltage level, which is not directly connectable to a typical mobile I/O device. A similar interface can also be implemented with sinusoidal signals.

3.2 Digital buses and networks

Digital communication has undisputable advantages compared to analogue signals: digital signals have a strong tolerance of interference and noise, it is possible to transfer several control signals and configuration data in one conductor, and transmission errors can be detected and corrected, for example. When arranged as a network, digital communication enables efficient distributed control and minimizes cabling.

A device with a digital interface has an embedded microprocessor (typically as the core of a microcontroller) unless both functionality and communication interface are simple. This makes the devices more expensive. On the other hand, as the computation of a system can be distributed, the main controller can be less expensive. The key problem with microprocessors, however, is their relatively short life cycle. There are different compilers, software development tools and hardware programming and debugging interfaces for each family of processors or microcontrollers. As workstation hardware and operating systems tend to become obsolete within a few years, maintaining configuration tools for older devices is often challenging.

Digital communication can be optimized for data rate, transfer delay, distance, cost or reliability. The solution is always a trade-off between some of these design parameters. Since one bus or network cannot be optimal for everything, there are dozens of standardized and established ways of digital communication. Furthermore, the rapid development of electronics and industrial competition constantly produce new digital buses and networks. Updated specifications are backwards compatible, in general, but the rapid introduction of entirely new buses and networks tends to make the older ones obsolete.

In addition to physical specifications, a communication protocol has to be defined. Depending on the system, different levels of the Open Systems Interconnection (OSI) model [55] are implemented. There are typically several competing higher layer protocols for each physical layer. Some of these protocols conflict with each other and therefore require separate physical layers.

Considering design, production and maintenance of mobile machines, it would be ideal to have the same digital interface for all devices. Due to application-specific optimization, many devices only have the interface that best suits the device type. Therefore, actual mobile machines with advanced automation include several digital buses and networks.

3.2.1 ISO 11898 (Controller Area Network)

CAN was originally developed for automotive applications. Since the control systems and operating conditions of cars and mobile machines are alike in many ways, CAN is nowadays the most common network in the distributed control of mobile machinery.

CAN cabling can be implemented at low cost as the only key parameter is a characteristic impedance of 120 Ω [96]. For most operating environments, unshielded twisted pair copper cable is sufficient. Care has to be taken, however, to minimize mismatches in characteristic impedance all over the network. Typical mismatch problems are related to connectors and termination.

CAN controller ICs implement the data link layer of the OSI model according to [96]. Most CAN controller ICs have a configurable data signalling rate up to 1 Mb/s. However, not all devices can take full advantage of this feature: An application layer protocol or the functionality of the device may require a certain rate. Moreover, the device may have a limited message processing capacity, which either restricts the maximum data signalling rate or tolerates only low bus loads at high data signalling rates. Because all the devices of a CAN need to have the same data signalling rate, this limitation alone may require dividing the devices of a system into several CANs. To utilize high bus loads, careful message scheduling is required [43].

The main limitation with CAN is the maximum data signalling rate of 1 Mb/s. Therefore, in a control system with several closed loops the data transfer capacity of CAN is often insufficient. Another problem in some control applications is that the common CAN protocols are not deterministic: a message with a higher priority may cause extra communication delay at any time. This can be avoided to some extent by careful node configuration and synchronous message transmission. [16] A deterministic time-triggered communication has been specified [98], but not widely implemented so far.

When CAN is operated at 1 Mb/s, the maximum bus length is only 25–40 m [16][97]. Since the bus topology requires short stubs, the trunk may become surprisingly long. An example of this is illustrated in Figure 11. Moreover, these distances can be reached with late bit sampling points, only. The chosen application layer protocol specifies the sampling point and thus maximum tolerance for the oscillator. For example, CANopen specification for sampling point is 75–87.5 % of nominal bit time [16]. For size or cost optimization, a system can be designed with devices that have more inaccurate oscillators. To enable sufficient resynchronization jumps in such conditions, the sampling point is set earlier, which results in maximum bus lengths shorter than specified [95]. In general, this is not good procedure because all the devices of the bus would have to be able to resynchronize to these inaccurately timed transmissions, and compatibility with most application layer protocols is thereby lost. The number of devices has a considerable effect on the bus length as well: devices need to be spaced sparsely enough to keep the mismatch of the bus characteristic impedance low [22]. If minor extra delays can be tolerated, some of the limitations can be avoided by grouping devices into separate buses and using CAN switches [99].

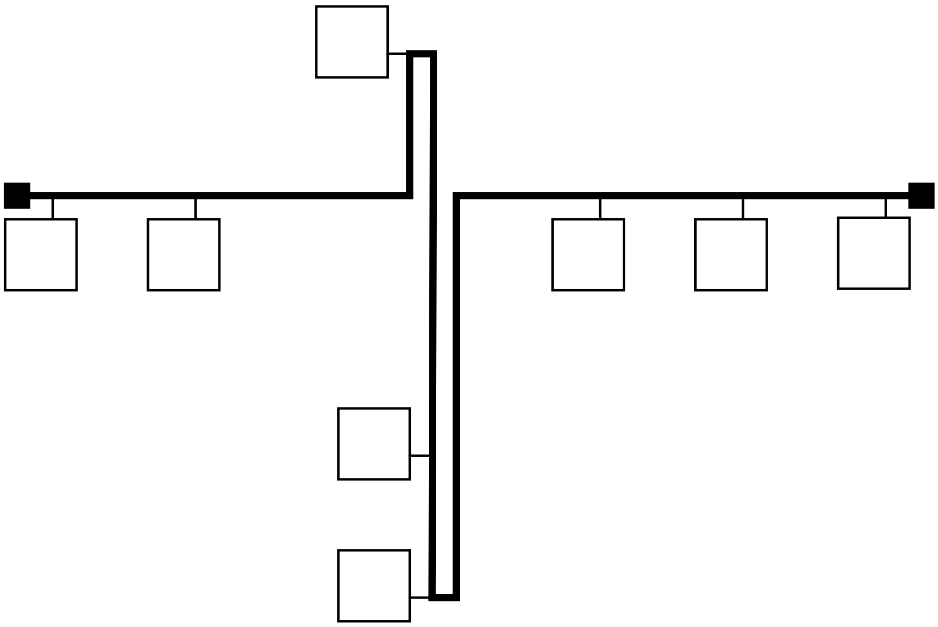

Figure 11. Example bus layout of CAN.

There are several application layer protocols that cannot usually be used in the same physical network. SAE J1939 is the only CAN protocol generally supported by heavy duty diesel engine manufacturers. Because J1939 was originally developed for trucks, it does not cover the communication of a machine, in general. Therefore, machines with such an engine often have one CAN for J1939 devices and another for controlling the hydraulic system, for example.

Some of the application layer protocols are designed to be more flexible. CANopen and Common Industrial Protocol (CIP) are the most common general-purpose CAN protocols. CANopen specifications are maintained by CAN in Automation (CiA). In addition to general protocol specification, CiA has defined profiles for several device types and applications. The specifications also cover system management process and interfaces between CANopen software tools. [87] Therefore, CANopen devices can be replaced with a similar product from another manufacturer rather easily. Conformance tests are not mandatory, which has contributed to extending the CANopen product range. On the other hand, some of the devices that have not been tested for conformance do not fully meet CANopen specifications.

CIP is the application layer protocol of DeviceNet which is managed by ODVA, Inc. The manufacturers of DeviceNet equipment are closely linked to ODVA to maintain product conformance. This, in contrast, makes developing new products more difficult. Most DeviceNet products are targeted at industrial automation.

Because a CAN frame is simple and networks of only a few devices are common, implementing light system-specific protocols is often fast and easy. However, considering the life cycle of mobile machines, a commonly used protocol makes maintaining and extending the control system more efficient. Because most application layer protocols have minimal overhead and flexible options for timing, system-specific protocols have no performance benefit.

Although CAN is the current industry standard in mobile machine control systems, it is likely to be eventually replaced with a faster network. CANopen and CIP are already available as deterministic real-time protocols on Ethernet, for example. [36][83] Moreover, a specification for CAN with flexible data rate (CAN FD) has been released recently. CAN FD networks can be built using the same cabling as CAN. Messages are sent using the same arbitration phase as CAN, with the same data signalling rates of up to 1 Mb/s. For data phase, however, the data rate can be higher, up to 8 Mb/s, and the number of data bytes can be as high as 64. With these measures, it is possible to achieve a much higher actual throughput. Moreover, as the length of the CAN FD bus trunk is only limited by the data signalling rate of the arbitration phase, it is possible to choose the two data rates so that both the actual throughput and the bus length are increased. If the flexible data rate is not used, CAN FD hardware is compatible with CAN. [32][46] Because CAN FD specification is rather new and there are new challenges regarding the physical implementation [47], there are no commercial transceivers supporting the highest flexible data rates yet [32].

Since classic CAN controllers would reject messages with flexible data rate, these controllers need to be disabled during flexible data rate communication. Therefore, systems with both classic CAN and CAN FD devices can have faster and more advanced firmware updates, testing and debugging features, etc. but there is no improvement in throughput during normal operation. It is, however, likely that standardization will change the behaviour of new classic CAN devices in the near future: CAN FD messages will be ignored instead of being flagged invalid [32][71]. This will enable transmitting of real-time signals over CAN FD in mixed systems. To make the transition to CAN FD easier, Lennartsson and Olsson propose an ‘enhanced format’ that interleaves extra data bits inside classic CAN frames. These frames would appear valid to all CAN controllers since the extra data bits are transmitted within a nominal bit time, sufficiently before the bit sampling point. [71]

3.2.2 IEEE 802.3 (Ethernet)

Ethernet is the most actively developed and supported local area network (LAN) technology. The development started in the 1970s and the first Ethernet standard was published in 1985 by the Institute of Electrical and Electronics Engineers (IEEE). The first implementations used a thick coaxial cable as the physical medium. Several new physical layers have been standardized since, but most specifications have remained valid. [57] In addition to ongoing strong development and standardization, Ethernet has an extremely strong position in the office, consumer and industrial markets. IEEE standards for Ethernet cover the physical and the data link layer of the OSI model [56][57]. Since Ethernet was originally developed for the office environment, there are features that are not optimal for industrial applications, not to mention mobile machines.

Nowadays, the physical layer of Ethernet is often implemented according to 100BASE-TX or 1000BASE-T specifications of [57]. The eight position eight contact (8P8C) modular connector that is used in these specifications has limited strain relief and poor protection against dust and water [20]. Although many manufacturers refer to this connector as registered jack 45 (RJ45), actual RJ45S and RJ45M specifications contain wiring configuration for telecommunication, using a keyed version of the 8P8C connector [82].

For 10BASE-T and 100BASE-TX there is an optional, properly protected industrial connector: a 4-pole M12 with D-coding. ‘Coding’ refers to mechanical keying that prevents the common A-coded 4-pole M12 sensor connectors from being accidentally mated with the D-coded M12 Ethernet connectors, for example. The 8-pole A-coded version of the same connector is used for 1000BASE-T. Even 10 Gigabit Ethernet is supported by several manufacturers with X-coded 8-pole M12 connectors that are actually not included in the M12 specification of the International Electrotechnical Commission (IEC). Because of this, some manufacturers prefer to call these CAT6A M12 connectors instead. [21][51, pp. 216–217][104, pp. 78–80] These connectors are not specified for Ethernet by IEEE, but especially the 4-pole version is strongly supported by several manufacturers of high protection rating Ethernet devices.

The 8P8C modular connector is, however, often the only option in an industrial device, probably due to strong standardization and low cost. With devices like this, an extra enclosure is needed if there is no dust and waterproof control cabinet available for installation. The connector type can be changed from 8P8C into M12 on the enclosure panel with an adapter, see Figure 12 [70, p. 45][100, p. 240][103, pp. 94–95]. However, even inside the extra enclosure, conventional

8P8C connectors are still vulnerable because of the mechanical vibrations and shocks of the machine. There are robust 8P8C products, but both the plug and the receptacle need to be of the same product series [14, pp. 46–51][103][104], they are more expensive and require more space than M12 connectors. Although there is a standard that specifies robust 8P8C connectors for industrial networks [54], various manufacturer-specific connectors are widely used. Most robust 8P8C receptacles, however, accept the regular 8P8C jack, which makes testing and configuration in clean and dry locations easier as no special cables are needed.

Figure 12. Adapters between M12 and 8P8C for panel installation [103, p. 94].

Excluding obsolete coaxial cable implementations, Ethernet typically has a star topology with a switch or a hub in the centre. A daisy chain is also possible if all the devices have two physical Ethernet ports. Regardless of the topology, the physical layer of Ethernet is more expensive to implement than CAN, for example.

At the moment there are not many Ethernet devices available for motion control of mobile machines. However, considering embedded computers, wireless communication modules and various advanced sensor systems, Ethernet is often the only reasonable option.

3.2.2.1 Internet protocol suite

The internet protocol suite (often called TCP/IP) is the most common set of protocols used in Ethernet systems. Although the internet protocol suite is a layered set of protocols, it does not strictly comply with the OSI model. Most of the suite is divided into application layer, transport layer, internet layer and link layer protocols. [94] These layers do not have strict definitions. Part of the data link layer of the OSI model is covered by the link layer of the internet protocol suite. One of the key protocols of the link layer is address resolution protocol (ARP) which finds an Ethernet address for a destination internet address. The pairs of Ethernet and internet addresses are stored into a translation table which is typically cleared at shutdown. Therefore, after boot-up, ARP communication takes place before the first transmission to each destination address. [35]

The main protocol of the internet layer is called internet protocol (IP). Its main functions are addressing and fragmentation of data packets from higher layers. IP has a header checksum which makes sure the packet is addressed and fragmented correctly. The data of the packet, however, is not checked for errors in this layer. IP has no mechanisms for acknowledgment, retransmission or flow control, either. [60]

Most application level protocols are based on transmission control protocol (TCP) [109] which corresponds to a transport layer protocol in the OSI model. As a connection-oriented protocol, it has features that are not needed in control applications. A more suitable option is another transport layer protocol, UDP. A lost or duplicated packet is not detected by UDP. [119] In a small, properly configured on-board network transmission, errors are unlikely and typically originate from a hardware fault. Therefore, a separate detection of fault situations is usually implemented.

3.2.2.2 Industrial Ethernet

Neither Ethernet specifications nor internet protocol suite definitions are deterministic: although frame collisions can be avoided by using switches instead of hubs, the communication delay cannot be predicted if the transmissions of several devices overlap. There are several competing solutions that implement a deterministic industrial Ethernet. Some of these, however, require modified Ethernet hardware. Some specifications are entirely based on proprietary network controllers; others work with IEEE 802.3 compliant controllers but achieve improved accuracy if modified controllers are used. Fortunately, the modified controllers required for accuracy enhancement are often IEEE 1588 compliant and used to implement hardware-assisted precision time protocol (PTP) that enables clock synchronization in sub-microsecond range. It is also possible to implement PTP with conventional IEEE 802.3 compliant network controllers and achieve synchronization accuracy of 20 µs, for example. [39] Some of the specifications that are implemented with standard Ethernet hardware are based on UDP, but most of them replace the entire internet protocol suite with a real-time protocol stack. Conventional internet protocols are, however, supported as the real-time protocol stacks have separate time slots for non-real-time communication. [37][38][45]

Many automation devices, nevertheless, still have only a standard Ethernet interface and support only the regular internet protocol suite. Therefore, it should be easy to add standard Ethernet devices into an industrial Ethernet system. Unfortunately, this is usually not the case. The networks that use non-standard hardware require a special bridge between the industrial and standard parts of the network. A bridge is also needed with an IEEE 802.3 compliant industrial Ethernet if the firmware of the standard Ethernet devices in the system cannot be updated.

Most industrial Ethernet devices are not designed to tolerate the operating conditions of mobile machines. However, as the level of automation is increasing, industrial Ethernet may well replace CAN in mobile machinery applications. Due to relatively long machine lifecycles and small production volumes, the industrial Ethernet protocols that are based on standard Ethernet hardware seem most applicable. For example, in CANopen-dominated applications POWERLINK is a likely successor, having the same application layer protocol [36]. If minimal cycle time and maximum protocol efficiency are required, EtherCAT may be preferred. Pickel et al. experimented on both POWERLINK and EtherCAT, and successfully demonstrated EtherCAT communication between a tractor and an implement. [88]

3.2.3 V.24-based serial link

V.24 and V.28 recommendations specify a serial link that was originally designed to interface a teletypewriter with a modem. The interface is often referred to as RS-232, according to the American national standard. For compatibility reasons, a V.24/V.28 compatible serial port was included in practically every personal computer till it was replaced by USB. The V.24/V.28 interface is light to process and the hardware is low-cost. Therefore, it is still common in embedded devices. The serial interface is controlled by a universal asynchronous receiver/transmitter (UART).

UARTs do not have addressing or error detection apart from rarely used simple bit parity check. Therefore, proprietary serial protocols are common. There are also several well-established protocol specifications for certain applications.

A V.24/V.28 serial link has a point-to-point topology. Therefore, a computer typically has a separate serial port for each V.24/V.28 device in the system. Maximum cable length depends mainly on the total capacitance of the cable. V.28 specifies single-ended signalling which is sensitive to interference. Therefore, especially long cables have to be shielded.

V.24/V.28 devices have quite low data rates. The V.28 recommendation covers data signalling rates only up to 20 kb/s [31], but devices supporting up to 115.2 kb/s are common nowadays. In any case, the maximum data signalling rate has to be checked for each device separately.

A point-to-point serial link can also use differential signalling according to V.11 specification [30], also referred to as RS-422. The specification enables longer cables and higher data signalling rates. Similar transceivers can also form a half-duplex multi-point network as specified by ISO/IEC 8482 [59], or RS-485, if the transmitters can be switched off. This type of serial bus is common in traditional industrial automation.

3.2.4 Local Interconnect Network

To complement automotive networking with CAN, for example, a low-cost technology called Local Interconnect Network (LIN) has been developed. In addition to protocol definition, LIN specification covers a work flow concept with configuration and node capability languages. An application programming interface (API) is also specified.

LIN can be implemented with the same UARTs that are used in V.24/V.28 serial links, only the bus driver/receiver circuitry is simpler. One common single-ended bus signal is used, making the cabling simple but also more sensitive to interference. LIN has a maximum data signalling rate of

20 kb/s, which limits its applicability. The maximum length of the bus is 40 m with a topology similar to CAN. [73] Using hubs, the length and topology could be extended [99].

Another limitation is that a LIN always has one master and up to 16 slaves. Although slaves can receive each other's frames directly, all the frame transfers are initiated by the master according to a schedule table. The header includes a sync byte that enables the use of inaccurate oscillators in the LIN slave devices. Thanks to master-initiated communication, a LIN can be configured to be deterministic. Because of these mechanisms the total overhead is, unfortunately, more than four bytes per frame. In addition, the LIN specification allows rather long inter-byte space, resulting in long frame slots in the schedule table.

Let us consider the actual throughput of a LIN system with slaves that are 8-bit sensors, transmitting frames that have one data byte. The actual throughput, R_t, can be calculated according to (1).

$$R_t = \frac{T_d}{T_{fs}} R_b \ , \tag{1}$$

where T_d is the length of sensor data, T_{fs} the length of a frame slot and R_b the data signalling rate. A frame header transmitted by the master is always 34 bits long, not taking into account possible inter-byte space. The slave then transmits one byte of data and a checksum byte. Bytes are transmitted similarly to UART communication, with one start and one stop bit. Thus, the response from the slave takes 20 nominal bit times. The nominal length of a frame with 1 byte of data is therefore 54 bits. The maximum length of a frame with inter-byte space is specified to be 140 % of the nominal transmission time, including bit timing tolerance. If the jitter in master task timing is not significant, each frame slot has to be at least 75.6 nominal bit times. [73]

Substituting T_d = 8 and T_{fs} = 75.6 to (1), we get

$$R_t = \frac{8}{75.6} R_b \approx 0.11 R_b \ . \tag{2}$$

Most networks have similar efficiencies when a frame carries minimal payload data because addressing and error checking typically form a fixed overhead. However, the problem is emphasized with LIN because R_b is low. Therefore, at the full data signalling rate of 20 kb/s, the network of 8-bit sensors would have a maximum throughput of only 2.1 kb/s.

Since LIN is targeted to be a low-cost technology for automotive manufacturers, commercially available LIN products are mainly automotive ICs, not robust I/O modules. However, slave I/O ICs can be used to develop simple generic I/O modules that can be configured according to the LIN work flow [79][111][112].

3.2.5 IEEE 1394

IEEE 1394 is a high-performance serial bus for computer peripherals, for example. Depending on interface generation, an IEEE 1394 interface uses a data signalling rate of up to 3.93 Gb/s. The interface is often called FireWire, according to the brand name of Apple Inc., the original developer. The specification includes different physical transfer mediums, but the most common is short-haul copper cable. It typically has a maximum length of 4.5 m, although longer cables are possible in simple network layouts. [49]

A short-haul IEEE 1394 network with more than two devices has to be daisy-chained or branched, using devices that have more than one port. In addition, since the cable shielding specification is quite complex, the hardware cost of a network easily becomes high. [49] The IEEE 1394 specification is targeted at indoor applications. There is no well-established industrial connector outside the specification, either. Therefore, protected and robust plugs and receptacles no not mate, in general, unless they are of the same product series.

If data signalling rates above 393.216 Mb/s are used, a 9-pin Beta or bilingual connector is required. Unfortunately, there are no protected variants of these connectors commercially available. In mobile machinery applications this means that both ends of a commercial Beta cable are likely to be routed through a sealed cable gland. Since the 9-pin connectors are rather bulky (diagonal typically 14–15 mm) in relation to typical Beta cable diameter (less than 7 mm) [49], most cable gland manufacturers do not have a gland with a suitable clamping range. It is also possible to choose the cable glands according to cable diameter and install one or both of the connectors after routing the cable. Unfortunately, installing the 9-pin connectors requires soldering or crimping. A solution like this is not flexible or convenient considering assembly or maintenance. Another option is to choose the cable gland according to connector diagonal and increase the diameter of the cable to ensure proper sealing. This can be done by applying heat shrink tubing that has a high shrink ratio, for example. Furthermore, the 9-pin cable may be fitted through solid tubing that has a sufficient diameter. Using cable glands, the solid tubing forms a sealed channel between the enclosures. Whichever the solution, extra effort is required.

An IEEE 1394 interface is not included in a typical embedded computer. A separate adapter board is therefore needed. Although an IEEE 1394 interface can be implemented with low-cost components, industrial grade adapter boards for embedded computers tend to be considerably more expensive.

3.2.6 Universal Serial Bus

USB was designed for interfacing peripherals with a personal computer. The latest version of the specification, USB 3.1, has a maximum data signalling rate of 10 Gb/s. At the moment, however, most devices only support USB 2.0, which has a maximum data signalling rate of 480 Mb/s. The

USB network has a tiered star topology, which requires a host that is connected to devices directly or via hubs. The devices do not communicate with each other but only with the host.

USB 3.0 has more complicated cable and connector specifications than USB 2.0. Neither specification states the maximum length of a cable, but only a limit for signal propagation delay and insertion loss. With typical cables, these result in a maximum length of a couple of metres. [113][114] In mobile machinery applications, USB has connector limitations similar to IEEE 1394.

3.3 Comparison of key parameters

Key parameters of the presented bus and network technologies are compiled in Table 2. The number of plus signs in the application programming interface (API) column is intended to give a relative impression of the extent of software support. The rating is based on driver or API availability for different operating systems likely to be used in automated mobile machinery, the estimated effort of writing a driver or API for unsupported operating systems, and the complexity of writing software using the API. It is also considered to be a clear advantage if the APIs of different vendors comply with a standardized or otherwise well-established specification. All of this applies to the communication interface itself but also the connected devices. The availability of different protocol stacks is also considered.

The ‘device availability’ column lists devices that are available with the network or bus interface in question. The lists are not exhaustive, but reflect the device types that are commonly used in automated mobile machines.

Table 2. Comparison of on-board data transfer solutions.

	Max data signalling rate	Max segment length	Physical topology	API	Device availability
CAN	1 Mb/s	25 m (CANopen at 1 Mb/s)	bus, active star	++	power train, PLC, general I/O, sensors, GNSS receivers, motion control, advanced automotive sensors
Ethernet	1 Gb/s (typical)	100 m	active star	+++	machine vision cameras, surveillance cameras, laser scanners, IEEE 802.11 devices, GNSS receivers, mass storage, PLC, general I/O, motion control, advanced sensors
V.24/V.28 serial	115200 kb/s (typical)	15 m (typical)	point-to-point	+++	GNSS receivers, radio modems, laser scanners, advanced sensors
LIN	20 kb/s	40 m	bus, active star	++	cabin controls, general I/O
IEEE 1394	983.04 Mb/s (typical)	4.5 m (typical)	active star, daisy chain	+	machine vision cameras, mass storage
USB	480 Mb/s (typical)	5 m (typical)	active star	+	mass storage, web cameras, machine vision cameras, GNSS receivers

3.4 Wireless data transfer

Wireless data transfer is required for direct teleoperation but also for communicating with an automatically operating machine. There are several wireless technologies that can be applied to mobile machinery. Some solutions include network functionality; others are intended for simple point-to-point applications. For some wireless technologies there is support for internet protocol suite or other advanced protocols; for others transceiver registers may have to be accessed directly.

Wireless transceivers are optimized for data signalling rate, range, reliability or communication delay. Some have configurable reception sensitivity and transmission power. Transceivers have integrated error detection, forward error correction or retransmission mechanisms. Some devices are targeted at mobile machinery applications; others require protective enclosures or modified power supplies. Some technologies are available as ICs or prototyping boards, only.

3.4.1 IEEE 802.11

IEEE 802.11–based wireless networks have high data signalling rates, reasonable ranges and are supported by various protocols. There are standalone client modules that typically connect to on-board Ethernet as well as wireless adapters that are installed to on-board computers. In general, wireless adapters can be configured more freely by software. On the other hand, standalone wireless modules are independent of the operating systems of on-board computers, straightforward to configure and to replace. 2.4 GHz versions of IEEE 802.11–based transceivers are, unfortunately, popular in numerous applications, making the frequency band unreliable in some working sites. Furthermore, there can be other devices besides the IEEE 802.11–compatible transmitting in the 2.4 GHz frequency band.

The range of an IEEE 802.11–based wireless network is affected by several factors. If there is a line of sight between the antennas of the machine and the wireless AP, ranges over 200 m are possible but network throughput can be heavily decreased already at 100 m [62]. The situation gets worse when the line of sight is lost. Therefore, several 802.11–based APs may be required to cover the working site of an automated machine.

Depending on application, fast roaming, or handoff, between APs may be needed. A procedure for fast roaming with encrypted IEEE 802.11 communication has been standardized by IEEE in 2008 [58] but proprietary solutions still exist. Different methods for vehicle use are compared by Kwak et al. As the AP is selected by the mobile node, the handoff performance depends mainly on the on-board hardware. Wireless adapters may support fast handoff directly or with updated driver software. Some proposed schemes even include using an on-board localization system to assist in fast handoff. [67]

Vernersson et al. have compared general-purpose and vehicular versions of IEEE 802.11 communication in a quarry environment, a likely application of an automated mobile machine. Although the vehicular IEEE 802.11p equipment has a lower data signalling rate, it provides higher range and reliability in the tests. [122] Furthermore, Demmel et al. demonstrate how the speed of the vehicle affects maximum range, communication delay and packet loss in IEEE 802.11p communication. The results imply the performance is affected very little when travelling at 50 km/h, for example. [24]

3.4.2 Radio modems

When a point-to-point wireless connection, high reliability or long range is required, a radio modem may be preferred over IEEE 802.11–based networking. Radio modems typically have a V.24/V.28 serial interface that enables connection to various simple embedded devices and PLCs. Moreover, radio modems are available with various carrier frequencies to avoid interference with other wireless traffic. Unfortunately, there are very limited license-exempt frequencies available and many of them have tight limits for transmission power and duty cycle [93]. Therefore, it is possible that a license is required to meet application or location specific requirements.

Although different models of radio modems typically have compatible serial interfaces, the wireless communication is often proprietary. Therefore, both radio modems of a point-to-point link may need to be similar. Although the radio modems can be interfaced with simple devices, some configuration work is required. Typically, the transmitter power has to be selected as well as receiver sensitivity. A cyclic redundancy check (CRC) algorithm may be implemented to reject received invalid data. Other optional features include addressing, forward error correction and networking functionality.

3.4.3 Embedded wireless transceivers

If short-range wireless communication is needed at minimal size or cost, an embedded transceiver module or IC may be used. With these devices, some circuit board design and a protective enclosure are required. Although there are modules and ICs that implement IEEE 802.11, Bluetooth, ZigBee and other standardized wireless communication, also proprietary transceivers exist. In addition to size and cost optimization, an embedded wireless module may be chosen to experiment with state-of-the-art technology: Embedded modules are often the first products that are commercially available when a new communication technology is released. The recently introduced IEEE 802.15.4-2011–based ultra-wide-band (UWB) modules are a good example [91].

As the embedded wireless modules are designed to be interfaced with a microcontroller, a serial peripheral interface (SPI), Inter-IC (I^2C) or UART is typically used. If the wireless module does not have an integrated antenna, the antenna signal has to be routed to an external antenna. Care has to be taken to maintain the characteristic impedance of the antenna terminal in circuit board design, in wiring inside the enclosure and in a possible panel connector. Especially with ICs, an impedance matching circuit is often needed to match an external antenna to the antenna terminal of the IC. If the module has an integrated antenna, the enclosure material and model have to be chosen carefully to minimize attenuation of the radio signal.

To interface a wireless module with the on-board control system of a machine, embedded software is needed. The requirements for the software depend heavily on the application and the features of the wireless module: sometimes simple data routing between CAN and SPI is sufficient; sometimes all the functions of a wireless network layer need to be implemented.

3.4.4 Mobile Internet access

In addition to voice calls and messaging, mobile networks provide Internet access. The main benefit in mobile machinery applications is that the mobile data terminal is able to communicate over the Internet without any local wireless AP. Therefore, no setup work is required for communication when a machine is moved to a new site, as long as the site is within the coverage of a mobile network.

Unfortunately, the network throughput can be less than 10 kb/s and communication delay can be several seconds if only general packet radio service (GPRS) is available. Moreover, the performance varies depending on other mobile communication and cell distance. The change can be considerable at handoff from one cell to another. [11] Fourth generation (4G) technologies enable much better performance, network throughput of several Mb/s and a communication delay of less than 30 ms. Nevertheless, the handoffs between cells can still have a considerable effect. [126]

3.5 Applying data transfer to automated mobile machine

A proposed utilization of the presented data transfer solutions in the control system of an automated mobile machine is presented in Figure 13. For distributing the computing of low-level controllers, CAN and Ethernet are the only feasible solutions with sufficient flexibility, robustness, and real-time performance. For mobile machine applications there are diesel engines, sensors, hydraulic valves and pumps, etc. available with an integrated CAN interface. Connecting similar devices to Ethernet has to be done through generic I/O modules with analogue, pulse, and on-off signals. With Ethernet, however, a much higher network throughput can be achieved. This makes it possible to distribute the entire computing and I/O of the low-level control system over a single Ethernet instead of several CANs.

Several embedded computers are required for navigation, perception and other high-level controllers. Ethernet is the most feasible network technology for communication between these computers due to performance, software support, and cost. Ethernet is also the most utilized solution for communication between embedded computers in the related research discussed in Chapter 1. To meet the data rate requirements listed in Table 1, at least 1000BASE-T has to be selected. Ethernet is a common interface in machine vision cameras, lidars, GNSS receivers and other sensors related to perception and navigation. Utilizing other digital buses is, however, mandatory when experimenting with specific sensor products.

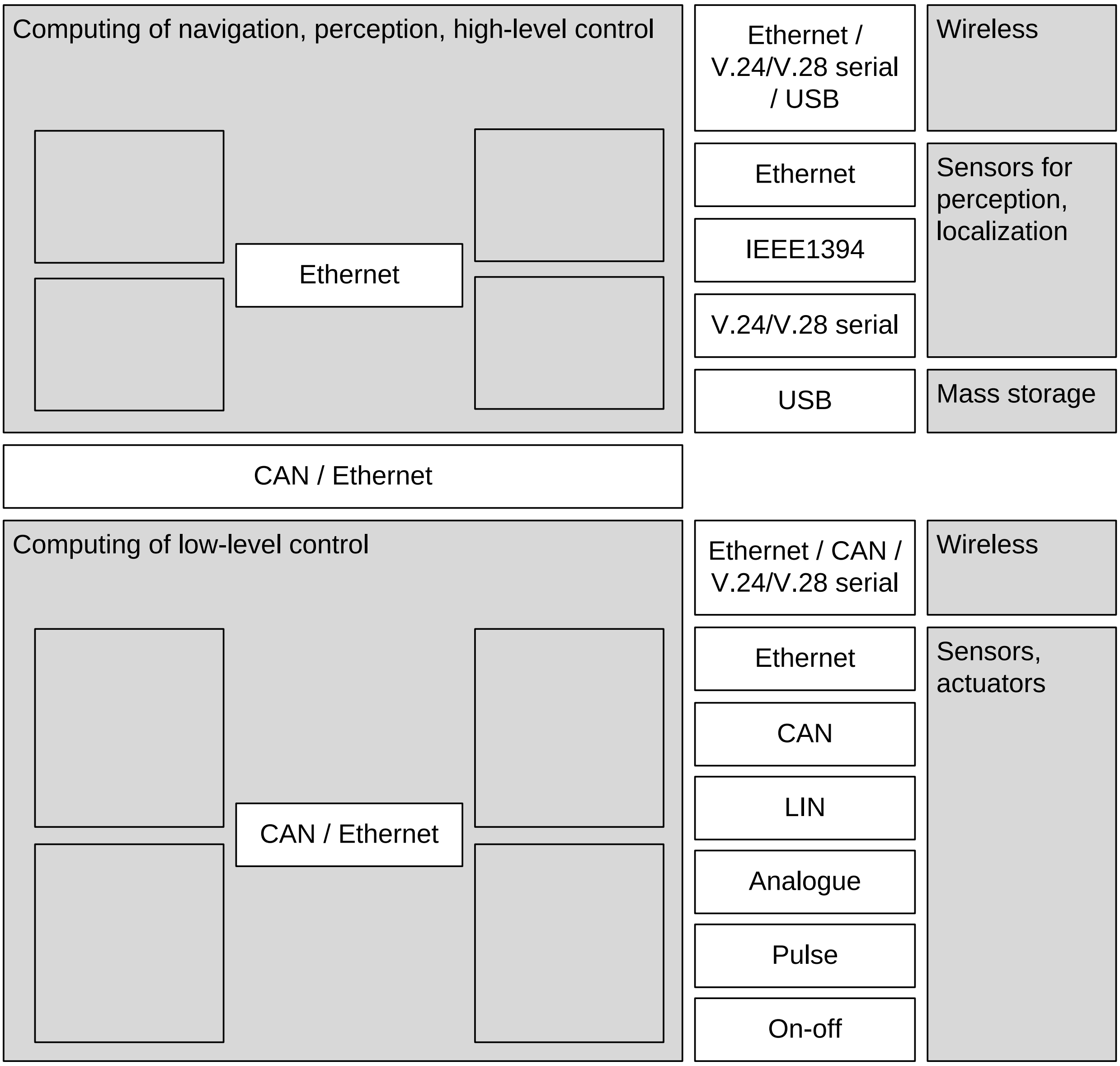

Figure 13. Proposed utilization of data transfer solutions.

4 Device-related design aspects

In this chapter, the design challenges related to typical devices in the electronic control systems of automated mobile machinery are presented and discussed.

4.1 Electrical power supply

The electric power to an electronic control system is usually supplied by the same battery and alternator that supply power to the starter and lights of the machine, at a minimum. As the electrical system in a typical manually operated machine has become more complex, more performance is also required of the batteries and alternators. Nevertheless, even the electric power supply of a modern manually operated machine may not be directly suitable for a control system that enables automated functionality.

4.1.1 Alternator

The control system of an automated machine has typically more electrical loads than its manually operated equivalent. Therefore, the maximum output power of a specific alternator will be reached more easily. This typically occurs after the electrical system has been operated without the engine running, discharging the battery. With an automated machine, this can be very common. The control system may wait for communication from fleet management, for example. In research and development machines this is even more common due to firmware updates, data logging, sensor system calibration, diagnostics, amongst others.

Exceeding the rated current of an alternator will decrease its life. The longer the overcurrent condition lasts and the more often it occurs, the more it will wear the alternator. Therefore, when choosing an alternator for an automated machine, it has to be taken into account that the battery may be notably discharged at an average start. Moreover, since the output current of an alternator is limited by its rotation speed, the entire output current of an undersized alternator may be consumed by the electrical loads in the system when the engine is idling, preventing the battery from being charged. Therefore, not only the nominal or maximum output current but also the output current when the engine is idling has to be considered when selecting an alternator.

4.1.2 Battery type

As mentioned above, the control system of an automated machine is operated for various reasons when the engine is not running. This has to be taken into account when defining the required capacity of the battery. For machines used in research and development, it is reasonable to have connectors for an external power supply to enable long tests without extreme oversizing of the battery.

The type of battery has to be chosen carefully. If the entire control system is not switched off when the engine is stalled, it has to be considered whether a battery that tolerates deep discharge is required. Moreover, the battery voltage should not drop below the supply voltage range of the control system during glowing and starting the engine. This is most likely to be a problem in 12 V systems, where traditional applications have permitted the range of battery voltage to reach quite low. For example, the lowest voltage of a 12 V starter battery in a standardized cold cranking test is specified to be 8.4 V [69]. Through reasons of size and cost, it is possible that the desired cranking performance or tolerance of deep discharge is not met. If the battery is not chosen according to these aspects, the characteristics of the chosen battery have to be taken into account when designing the control system.

Both problems can be solved at system level or by choosing every component according to the characteristics of the battery. At system level, deep discharge can be prevented by using a protective device that triggers an alarm when the battery voltage drops too low. If the alarm is ignored, power is eventually switched off. Likewise, the drop in the battery voltage due to starting can be tolerated by using a separate battery or capacitor that supplies power during cranking or until the voltage of the main battery circuit has returned to an acceptable level.

The two arrangements for deep discharge protection are presented in Figure 14. The upper diagram shows a system with an external protector that can be a separate standalone device. It is also possible to implement this functionality with a PLC that has suitable I/O. The same PLC can also perform other functions in the control system. This can decrease overall hardware costs, but what is more important, using a generic PLC can also improve life-cycle manageability. It is, however, critical that the PLC has minimal power consumption when the deep discharge protection becomes active.

Devices 1 and 2 are signalled before the battery is disconnected and perform a coordinated shutdown or a transition into a low-power mode. There are also devices that do not have a low-power mode and tolerate a sudden loss of power. Device 3 is an example of such a device and therefore requires no prior indication from the protector. The lower diagram shows a system with devices that have internal protection circuitry against deep discharge. Since each protection circuit operates independently, it has to be confirmed that the devices can be shut down in any order without causing undesired, or even dangerous, operation.

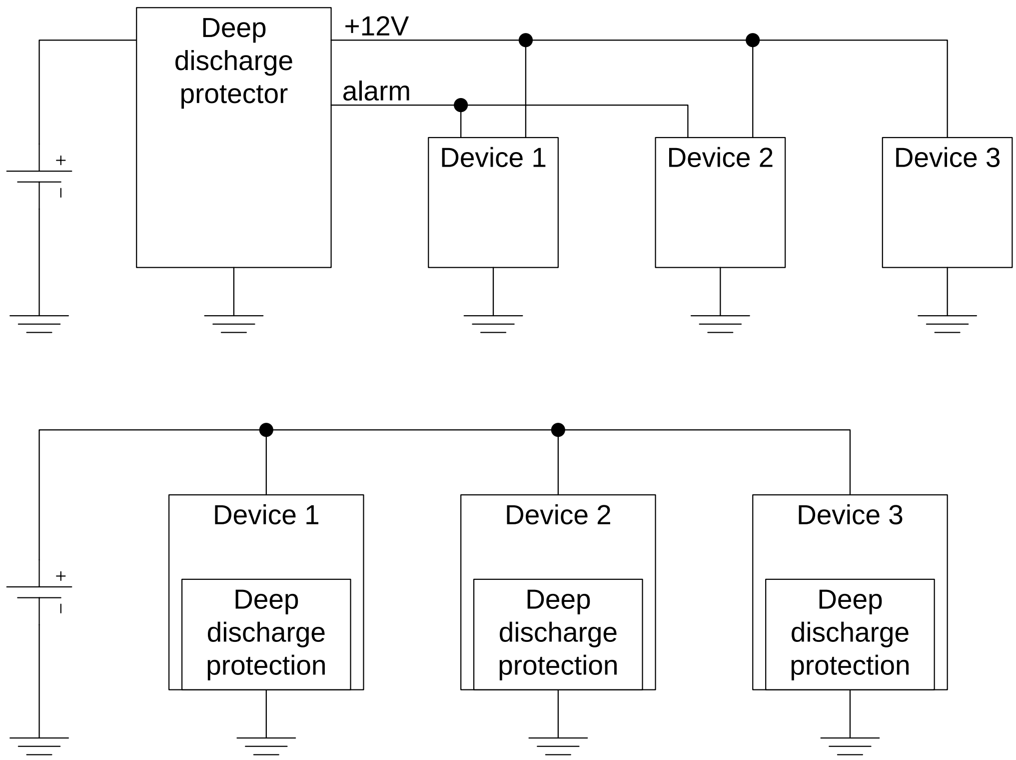

Figure 14. Two arrangements for deep discharge protection.

If all the devices of the control system accept a wide supply voltage range and have internal deep discharge protection, almost any battery type is suitable, even without external circuitry. Unfortunately, this is usually not the case. Regardless of whether the system level solutions described above are utilized, controlling the power states of the electrical devices have to be considered. The control system could, for example, command applicable sensors and actuators to a low-power mode by default when the engine is stalled. The devices that are sensitive to cranking could be treated similarly when the engine is started. If some of these devices are needed during cranking, they can be supplied by a boost type voltage regulator. With these measures, the battery life and operating time without the engine running are maximized. Moreover, the separate power supply to be used during cranking can be minimized, if needed at all.

4.1.3 Nominal battery voltage and DC/DC conversion

The nominal voltage of the battery system also has to be specified. Depending on the type and size of the machine, the electrical system of the manually controlled equivalent may be the only reasonable starting point. There may be essential electrical actuators or sensors that are only available for a 12 V system, for example. In general, 24 V is a widely supported supply voltage in both automation and mobile machines, apart from small machines with a 12 V system. The use of automotive components also promotes a 12 V system.

A possible process of specifying the battery system voltage is presented in Figure 15, assuming the selection has to be made between 12 V and 24 V. The process aims at minimizing the size and cost of the system as well as conversion losses. First, the devices of the control system are classified by supply voltage. Since the actual voltage of a battery varies between the low cranking voltage of a partially discharged battery and the maximum output voltage of the alternator, many devices that are not intended for mobile machinery or automotive applications cannot be powered directly from the battery. Devices like this need to be supplied by a separate voltage regulating direct-current-to-direct-current (DC/DC) converter. In the flow chart these devices are classified with the opposite voltage: 12 V unregulated with 24 V regulated and vice versa. This is done because a *non-isolating* DC/DC converter that has either a step-up or a step-down function is smaller, simpler and has a lower cost than a converter that performs both functions. This more complex converter type is required if a regulated 24 V supply is converted from a battery voltage of 24 V, for example. On the other hand, if an *isolating* DC/DC converter is used, there is no extra cost for having the output voltage within the input voltage range. In this case, the devices that require a regulated supply can be left out when making the decision about the nominal voltage of the battery system.

Depending on the application, isolating DC/DC converters may be required to protect sensitive equipment from different ground potentials, for example. To create an isolated section, the signal paths that cross the boundary of the section have to be isolated as well. Another reason for choosing an isolated converter is that DC/DC converters with sufficient mechanical and electrical robustness are not always available as non-isolated versions. In this case, the ground terminals of the input and the output side of the isolating DC/DC converter can be tied together if a common ground is required.

Some devices have a wide supply voltage range: 6–40 V, for example. Although the range of the supply voltage can reach rather high, most devices have internal circuitry that has a lower, regulated operating voltage. If the internal regulated power supply for this circuitry is implemented with a linear voltage regulator, the efficiency of the device decreases as the supply voltage is increased. Performance or maximum operating temperature may therefore be higher if the external supply voltage is lower. Even the efficiency of switched-mode voltage regulators depends on input voltage.

If there is no clear supply voltage dependence in performance, devices with a wide supply voltage range can be classified into class A or class B. The same applies to devices that are available as different versions with different nominal supply voltages. The flowchart in Figure 15 tests whether a majority of the electrical load can be concentrated to a single battery with either nominal voltage.

‘Combined maximum power’ refers to the peak power consumption of all the devices of a class. This is not equal to the sum of the device-specific peak power consumptions unless the devices may actually operate simultaneously at full power. ‘Combined average power’, on the other hand, is the average power consumption of all the devices of a class which is equal to the sum of the device-specific average power consumptions.

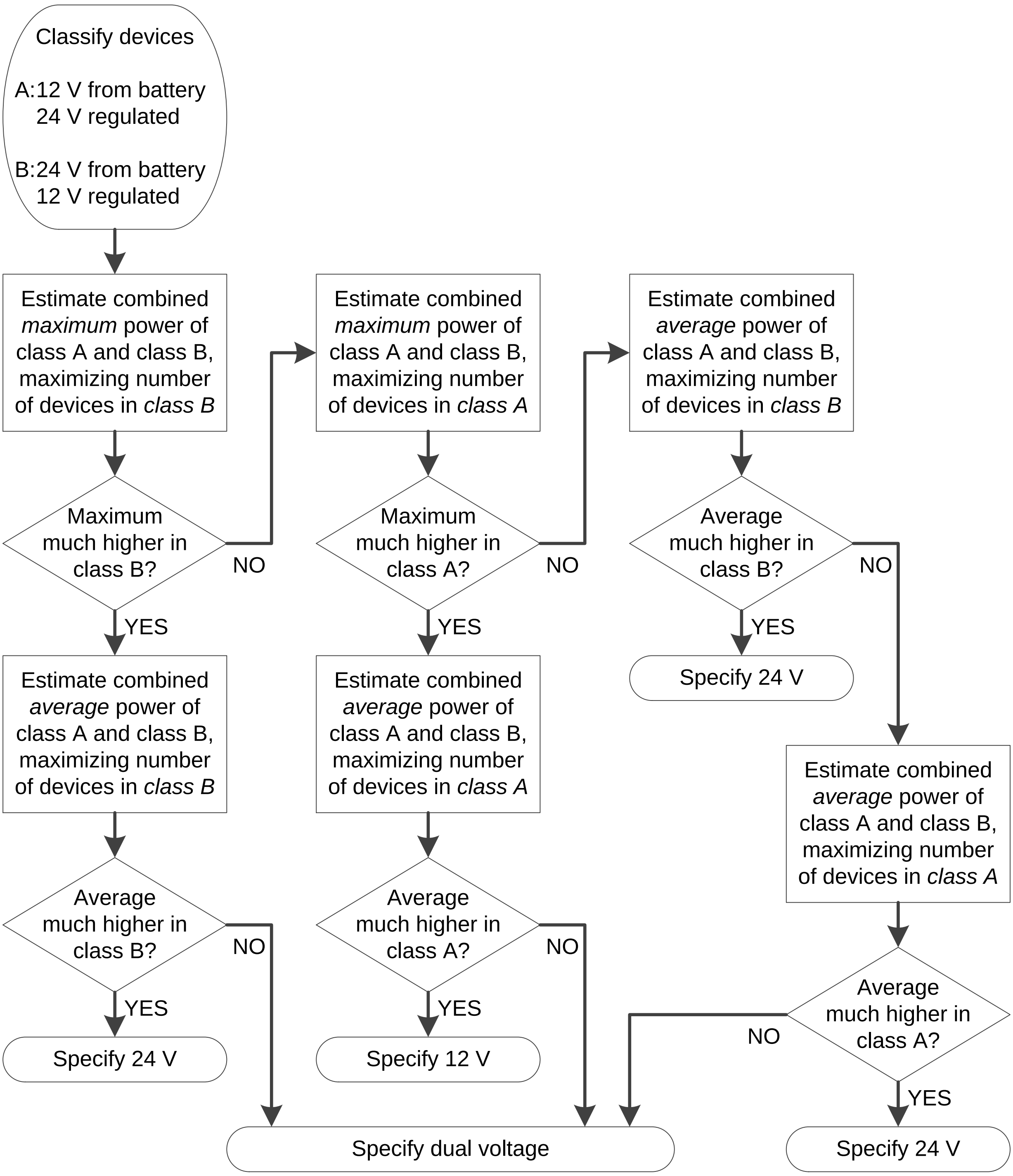

Figure 15. Workflow for specifying battery system voltage.

‘Dual voltage’ in Figure 15 refers to a battery system that has two separate power supplies. This can be implemented with two alternators, one supplying a 12 V system, the other supplying a 24 V system. It is also feasible to have one alternator, one battery and a heavy-duty DC/DC converter instead if the total power consumption is sufficiently low. In this case, the converter can be a simple voltage doubling or dividing power supply without voltage regulation, unless most power is consumed by devices that require a regulated power supply. Dual-alternator systems are not common in commercial machines as these systems require more maintenance and more space. However, the solution is reasonable in a machine utilized as a research platform where various devices need to be tested and the delivery time or price of a high-power device with an optimal supply voltage is not acceptable.

In most cases, it is possible to concentrate the electrical load to a single battery. For example, if the result is a 12 V battery system, the devices of class B are likely to have a low combined maximum and average power. A power distribution system like this is presented in Figure 16. In this case, the voltage regulating DC/DC converter can be specified to also supply 24 V devices that do not necessarily require a regulated power supply. If there are devices that require a regulated 12 V supply, another voltage regulator is needed. It can be powered either from a 12 V battery or regulated 24 V supply. If the converter is supplied by the battery, a more complex 12 V-to-12 V converter is required. On the other hand, if there are two DC/DC converters in series, the overall efficiency is lower and the total output current required of the 12 V-to-24 V converter is higher.

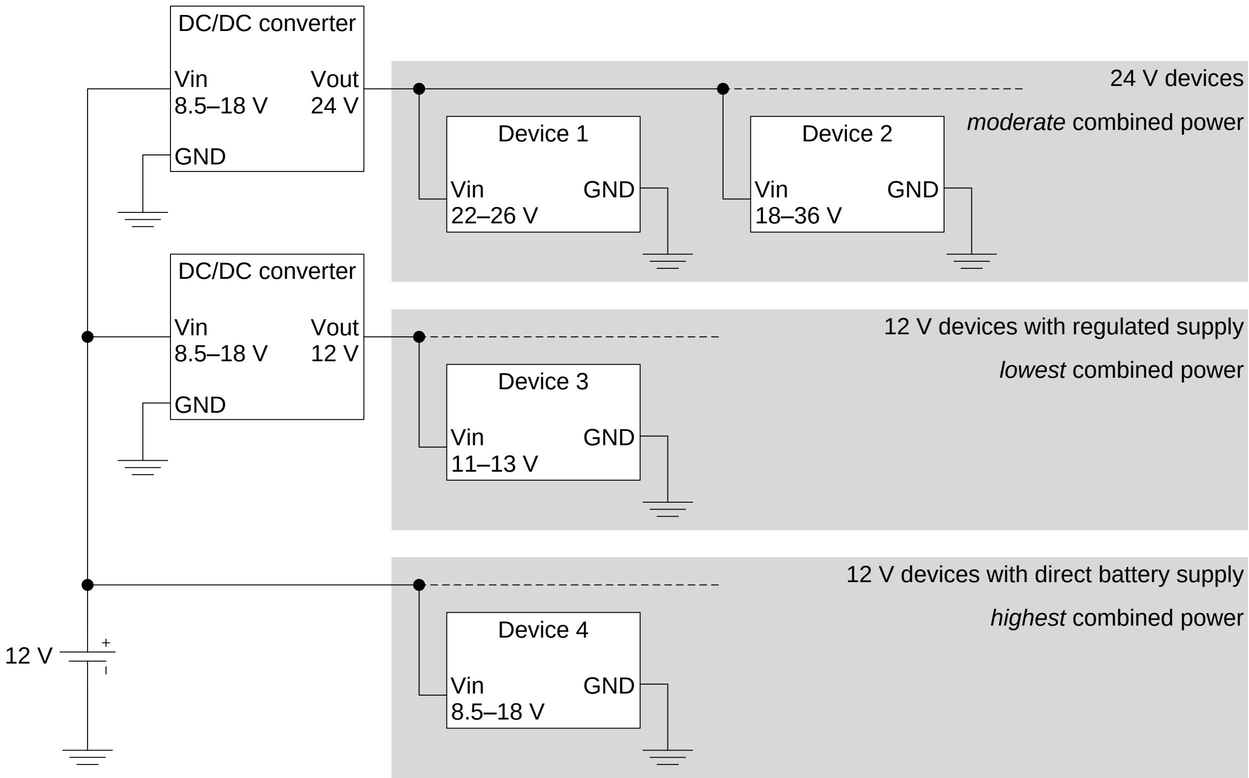

Figure 16. Example of power distribution.

4.1.4 Switch-off

As described above, the power consumption of the electronic control system has to be minimized when the engine is not running. Even more important is that the battery is not discharged when the control system is switched off. This can be done by controlling a battery isolator relay directly with the ignition lock or a main switch. Some devices, however, do not tolerate sudden loss of power supply. This sensitivity is typically related to storing data during operation. For example, a write operation to a flash memory must not be interrupted to ensure data consistency. Unfortunately, flash memory has to be erased in most cases before the write cycle, and erasure is only possible by pages. Therefore, modifying a single byte requires erasing and rewriting several bytes. For example, the worst-case duration of the write sequence to internal data flash with a Freescale 56F8323 microcontroller is over 25 ms, consisting of a 512-byte page erasure and 256 consecutive 16-bit write operations. [1][2]

Since the flash write sequence is rather short and does not consume much power, the problem can be avoided at device level by monitoring the external supply voltage and preventing write cycles to flash if the voltage falls too low [33]. If this happens in the middle of the write cycle, the internal capacitors of the device have sufficient energy stored for completing the cycle.

Not all sensitive devices have a built-in mechanism for surviving the sudden loss of power. Some cannot react as rapidly as simple microcontroller devices. Embedded computers with full-scale operating systems perform shutdown scripts to prevent file system errors and to ensure proper boot-up next time. Running these scripts sometimes takes several minutes. In this case, the energy needed for completing a shutdown script cannot be stored in a reasonably sized capacitor. One solution is to use a UPS that continues to supply power from its battery when the main battery is disconnected. There are UPS devices with both internal and external batteries. A UPS monitors the external supply voltage and the charge level of its battery. When either of these drops below a set limit, the devices supplied by the UPS are signalled. It is therefore not mandatory to start the shutdown process immediately when the main battery is disconnected. The protected equipment can, for example, monitor a set time whether the main power is restored.

UPSs are available as computer expansion boards and separate devices [84][115][120]. A UPS expansion board is feasible when a single embedded computer is the only sensitive device in the control system. Moreover, in research use one embedded computer may be moved between different control systems and test setups. In this case, it is a clear advantage if the computer has an internal UPS. When several devices are to be protected, a separate UPS is a feasible, modular solution. To minimize hardware and maintenance costs, it is also possible to protect sensitive devices without an extra UPS battery. Different solutions are presented in Figure 17.

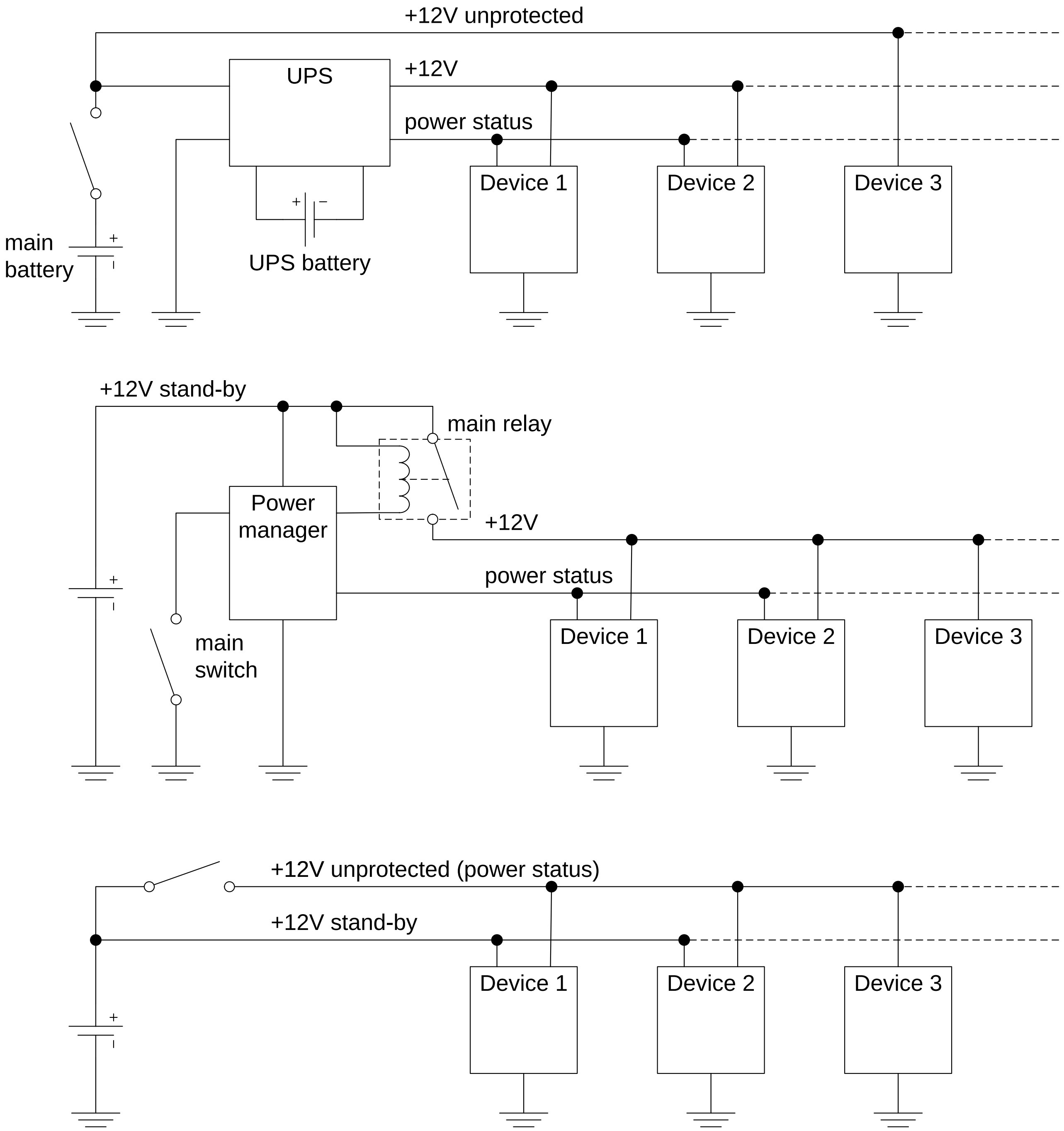

Figure 17. Three solutions to protect sensitive devices from sudden loss of power.

The top diagram in Figure 17 shows power distribution with a UPS. In this case, the UPS is a separate device that has an external battery. The ‘power status’ is a digital bus that communicates at least three states: *main battery connected*, *running on UPS battery*, and *UPS battery almost fully discharged*. In the middle diagram, a delayed main relay is utilized. The power management module, which is either a separate device or one of the PLCs of the control system, monitors the position of the main switch. The module outputs a ‘power status’ signal that typically has two states: *normal operation* and *initiate shutdown*. The latter becomes active when the main switch is opened. After a set time, the main relay is opened. In this case, the stand-by power consumption of the power management module has to be extremely low as the module is never disconnected from the battery. Moreover, the module has to recover from its low-power state when the main switch is closed again. The bottom diagram is simple but sets special requirements for sensitive devices: in this case, the sensitive devices themselves need to have minimal stand-by power consumption. Moreover, they need to switch to the low-power state reliably. The shutdown is now controlled directly by the main switch: when the power supply to unprotected devices is disconnected, the shutdown process has to be initiated. For embedded computers, there are automotive power supply modules that fulfil these requirements and switch to a low-power mode after a set time, even if the shutdown process of the embedded computer fails [74].

It is possible to utilize a device without a low-power state as the power management module with the circuit presented in Figure 18. In this case, all the devices, including the power manager module, are powered through the main relay. To switch the system on, a double-pole main switch is utilized: one of the poles controls the main relay in parallel with the power manager module. The other pole signals the power manager to initiate shutdown when the main switch is opened. With this approach, the power management functionality may even be distributed between several devices of the control system as long as the implementation is reliable. All the diagrams of Figure 17 and Figure 18 include a 'device 3' as an example of how a device that tolerates sudden loss of power is connected. When utilizing a power manager, the 'device 3' consumes power, while the sensitive devices perform a shutdown process. If this power consumption is significant, an extra pole of the main switch can be utilized for controlling the power supply to 'device 3' directly.

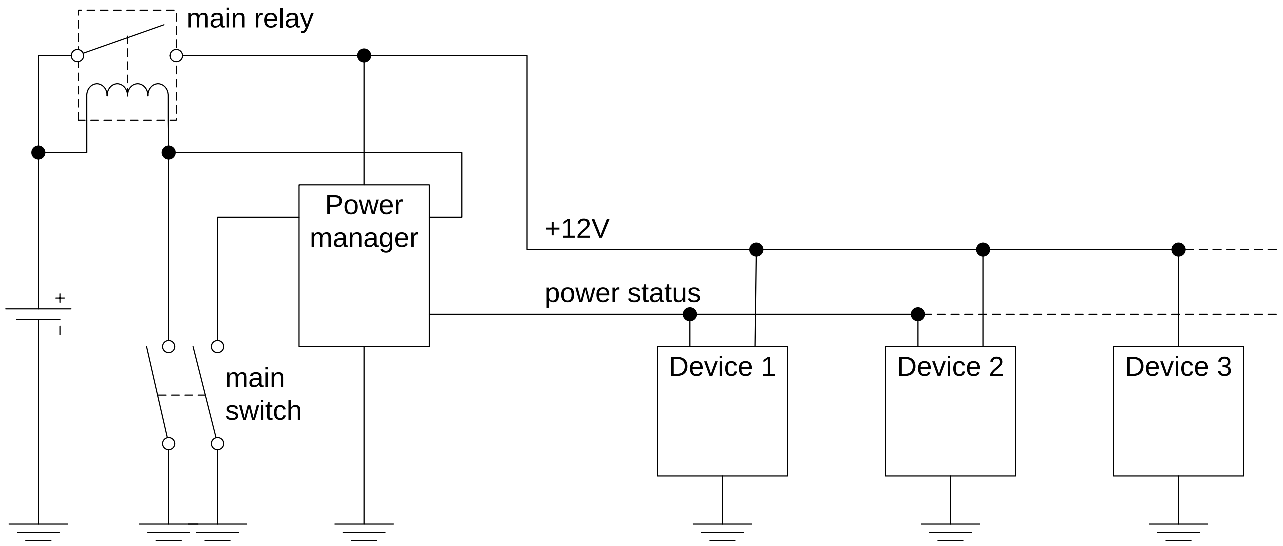

Figure 18. Arrangement with power management module without low-power state.

4.2 PLCs and I/O modules

Mobile PLCs and modular I/O systems have replaced mechanical pilot controls in many manually operated machines. As stated in Chapter 2, an automated machine needs to have electrically controlled functionality. This can be implemented with similar PLCs and I/O modules such as modern manually operated machinery. There are, however, some extra requirements: typically, the control system of an automated machine has more sensors and more closed loop control. Even if the number of sensors is not increased, higher sampling rates and resolutions may be required from ADCs. There is typically more on-board communication between PLCs, I/O modules, sensors and actuators. Furthermore, the allowed communication delay may be smaller, and more accurate synchronization of events may be required. To meet the requirements, the devices may need to be grouped into several physical networks.

4.2.1 I/O modules

As the number of sensors, actuators and networks is increased, more analogue and digital I/Os are needed and more complex hardware architectures required. It also has to be considered that the control system may need to be extended during the life cycle of the machine. The benefits of a modular solution and a standardized design and management process are therefore emphasized.

Modular I/O systems are typically based on slave devices that may perform simple signal processing in addition to basic I/O functionality. Depending on the physical construction of the machine, these I/O modules are physically distributed across the machine or located centrally in a cabinet. If a protective cabinet is used, the I/O modules can have a lower degree of protection and the number of commercially available modules, physical networks and protocols is therefore much higher. On the other hand, the wire harness becomes complex if most sensors and actuators are not next to the cabinet.

Since an automated machine may contain devices that are not intended for mobile machinery applications, the I/O interface on some of these devices differs from conventional sensors and actuators. Typically, mobile I/O modules are optimized for robustness: inputs have low impedances, low sampling rates and high decision levels. Outputs have low impedances and voltage levels close to the supply voltage. Push-pull outputs are available, but a typical on-off output has either a low-side or a high-side driver. Analogue inputs typically have measuring ranges for positive current and voltage signals, only.

For example, a sensor may have an on-off or pulse output that is implemented with a 5 V push-pull circuit. Because of the high decision levels, 5 V may be interpreted as the logical low state. In a similar way, a device may have an on-off input with a pull-down resistor and a specified maximum voltage of 6 V. Because of the output voltage level of around 14 or 28 V, a typical I/O module cannot control a device like this directly. Even if the I/O module has a low-side driver without an internal pull-up resistor to the high supply voltage, an external pull-up to 5 V, for example, has to be implemented. The use of generic I/O modules in the control system of an automated machine may therefore require several signal converters, amplifiers or simple external circuits with resistors, transistors and zener diodes. Especially with the physically distributed approach, these converters and circuitry require several extra enclosures.

I/O modules typically have a microcontroller for implementing a network interface. The same microcontroller may perform digital filtering for inputs, for example. If the microcontroller has a low computing capacity, it may not be able to process all the communication under high network loads. Each I/O module type considered for a control system therefore has to be tested with high data rates and network loads before deciding whether it is suitable.

4.2.2 Mobile PLCs

Although an automated machine may require embedded computers for calculating the algorithms of automated functionality, it is often not practicable to have the computers communicating directly with all the I/O modules. As communication with the I/O modules consists of small data packets that are transmitted at short intervals, computing capacity would be consumed by network traffic processing. The logical functionality of a manually operated machine is implemented with a mobile PLC, instead. The same PLCs can also be used in automated machines. Since PLCs often have several interfaces for CAN and other networks, they can communicate with other PLCs, slave I/O modules, other networked devices, and the embedded computers.

As PLCs are suitable for real-time control at short control steps, and some even have an FPU, they are an appropriate platform for calculating low-level functions. These include position control of hydraulic actuators and AFS angle, and travel velocity control by controlling the diesel engine and the components of the power train. A PLC may also be used to synchronize events. Although PLCs are available from many vendors, most of the devices can be programmed with IEC 61131-3 compliant software development tools.

4.3 Computing automated functions

It is reasonable to calculate on board at least some of the algorithms that are required for automated functionality. This applies, in particular, to real-time calculation and processing of high-bandwidth sensor data. Although some PLCs have sufficient computing capacity for simple automated functions, typically, embedded computers are required. Some sensors also require complex driver software or physical interfaces that are only available for embedded computers with an expansion bus.

Depending on the application, several embedded computers may be required. For example, real-time processing of high resolution images may consume all the available performance of a dedicated computer. Especially in experimental systems, several computers also enable efficient simultaneous development of different subsystems. Furthermore, several different operating systems may be needed on-board. The need can be related to different real-time requirements, driver support, available software libraries, and preferred tools for software development and testing [124].

In general, embedded computers are compatible with laptop and desktop computers: the same processor families, expansion buses, operating systems and even some peripheral devices are used. The dimensions or expansion bus connectors are, however, different. Several specifications for different physical platforms have been released with different emphasis on cost, size, mechanical robustness and performance [29][34][78][89]. The expansion boards of desktop or laptop computers are therefore not mechanically compatible with many of these specifications [29][34][89]. Therefore, the selection of the physical platform has to be made by considering the available expansion boards, as well.

4.3.1 Power supply and thermal design

Desktop computers have a well-established power supply specification according to Advanced Technology eXtended (ATX) documentation [8, pp. 19–22]. The ATX power connector is also one of the recommended connectors in the Embedded Platform for Industrial Computing (EPIC) specification, for example [34, p. 16]. The ATX power connector, however, is rather large and the required power supply is rather complex with several regulated voltage outputs. Although there are automotive versions of ATX power supplies available [74], an embedded computer may have a simpler power connector; some even operate from a single-voltage supply. As the power supply specifications are not strict, there are several different solutions between manufacturers and models. In addition to supplying the embedded computer itself, the expansion boards and other peripherals need to be considered: the total power consumption may increase considerably with these devices installed. Moreover, even if the computer itself operates from a single-voltage supply, it does not necessarily generate all the regulated supply voltages for the expansion buses.

Although embedded computers have lower power consumption than desktop computers, thermal design may still be a challenge. Embedded computers are often available as conduction cooled versions. Without a fan it is easier to make the enclosure of the computer water and dust proof. Nevertheless, a fan or other additional cooling is required if the installation location of the computer does not enable sufficient thermal conduction or the ambient temperature is too high. This is even more likely with high-performance embedded computers. It may therefore be feasible to distribute the computing over several lower-performance computers that can be cooled by thermal conduction. If a fan is used, air filtering is often required to achieve a sufficient degree of protection for the enclosure, unfortunately increasing the need of maintenance.

4.3.2 Mass storage

Although some embedded computers include soldered flash memory, external mass storage is often needed. In machinery applications, flash-based solid state drives (SSD) are a feasible option, tolerating mechanical shocks and vibration. In addition to conventional buses for internal mass storage, an embedded computer typically has a socket for a flash memory card. Furthermore, practically all embedded computers support USB mass storage. In many cases it is possible to boot the computer from a memory card or a USB flash drive, removing the need for an actual SSD entirely.

Commercial grade memory cards and USB flash drives are not designed to tolerate the operating conditions of mobile machinery. In addition, the reliability and endurance of commercial grade flash ICs may be insufficient. Even industrial grade memory cards and USB flash drives perform as a system drive slower than devices that are actually designed to be system drives. SSDs are available for system drive use with optimized internal cache RAM and with industrial grade ICs, for example. Nevertheless, there are differences in wear-levelling solutions and system drive performance between SSD models, as well. In case neither the operating system nor the applications write data on the system drive, the effect of write speed and write cycle endurance may be ignored. This can, however, limit the flexibility of the system.

4.3.3 Remote access

Since embedded computers are compatible with conventional peripherals, it is typically possible to install an operating system and application software by plugging in applicable USB devices and a display. This approach, however, is typically not convenient for accessing the computer after it has been installed on a machine. Access may be needed for updating the operating system or application software, testing, starting on-board data logging or downloading logged data. On some systems, the applications are even compiled on-board.

If the computer has a network interface, remote access software can be used. In this case, a network patch cable is connected either directly to the computer or to a network switch. If there is a wireless connection, a remote accessing computer can be located more freely. In case there is no remote access software available for the operating system, the files on local mass storage can be managed by booting the computer to another operating system that enables remote access. This is possible over a network or by plugging in an external system drive. To enable this, the boot sequence of the basic input output system (BIOS) has to be set up accordingly.

On some operating systems, remote access is possible through a V.24/V.28 serial link. Because of the modest data rate, it is appropriate to use a simple text-based terminal and transfer only sub-megabyte files. In this case, it may be feasible to transfer larger files with removable mass storage, typically a USB flash disk. If there is a need to change the BIOS settings, the V.24/V.28 serial link may be the only option in addition to keyboard and display, especially if the operating system does not start or permit remote access.

In research applications, it is likely that remote access is needed frequently. Depending on the installation location of a computer, some of the physical interfaces discussed above should be made easily accessible, even if they are not used in normal operation. If the enclosure of the computer has to be opened to reach the connectors, it also limits the environmental conditions where maintenance can be done. Panel connectors with a sufficient degree of protection are therefore reasonable, although they are often bulky and sometimes lead to choosing a larger enclosure. Furthermore, the panel connectors typically need a dust cap to maintain protection when they are not mated.

4.4 Pose estimation

Regardless of the application of an automated machine, it is common that the machine is intended to travel without a human operator on board. To implement path following, the machine has to perform pose estimation, that is, estimate its position and orientation in relation to a reference frame. Since the reference frame, bandwidth, reliability and accuracy vary between sensor types, data fusion from several devices is typically applied.

4.4.1 Global navigation satellite system receivers

A GNSS receiver enables the global position of a machine to be estimated practically anywhere in the world without any local infrastructure. The antenna of the GNSS receiver, however, has to have a line of sight to several satellites, which limits the number of feasible applications. Nevertheless, if the signals from a sufficient number of satellites can be received only occasionally, a GNSS receiver can still be used together with other pose estimation sensors. At the moment, there are two operational global systems, the Global Positioning System (GPS) system operated by the U.S. Air Force and Global Navigation Satellite System (GLONASS) operated by the Russian Aerospace Defence Forces.

Probably due to the long history of GNSS applications in well-standardized maritime electronics, practically all GNSS receivers are able to output NMEA 0183–compliant messages, typically over a V.24/V.28 serial interface. If this interface is used, replacing a GNSS receiver can be straightforward. Since the NMEA 0183 interface has a rather low data signalling rate and inefficient message format, GNSS receiver manufacturers have developed proprietary binary protocols, especially for RTK use. Receivers also have faster and more reliable interfaces for communication: A SAE J1939–based NMEA 2000 interface is a well-established way of implementing CAN communication into a GNSS receiver. Several protocols, mainly proprietary, also exist for Ethernet communication. NMEA has released plans to extend NMEA 2000 with an NMEA OneNet specification which could become the universal protocol for GNSS communication over the internet protocol suite [61].

In addition to outputting position data, differential GNSS receivers are also able to receive the data for differential corrections. The correction data is typically transmitted over a V.24/V.28 serial link with a protocol specified by the Radio Technical Commission for Maritime Services (RTCM). There are different versions of the RTCM protocol and a typical GNSS receiver firmware only supports some of them. The required protocol version typically depends on whether the GNSS receiver is an RTK device or a code-differential receiver. If the correction service is provided via the Internet, the data is usually transmitted as Networked Transport of RTCM via Internet Protocol (Ntrip). A differential GNSS receiver with an Ethernet interface therefore often has Ntrip client functionality.

Due to satellite orbit and clock errors and spatially and temporally variable satellite-to-earth communication delay, a GNSS receiver achieves only an accuracy of several metres unless these error sources are compensated. Most of the effect of the communication delay can be cancelled by dual-band reception because the ionospheric delay depends on carrier frequency. Dual-band receivers are more expensive, however, and still need to compensate for orbit and clock errors. Since the total error varies with time and receiver location, a fixed reference receiver can be set up near the site as a base station to cancel the error. Some GNSS receivers have an internal wireless module for receiving the differential corrections from a local base station. However, not all internal radios are compatible and they may have insufficient range. External radio modems can be applied in these cases as most differential GNSS receivers accept the correction data via V.24/V.28 serial port. It is also possible to use a modem for mobile networks for point-to-point communication or even Ntrip over mobile Internet.

The accuracy of the differential GNSS declines as the distance to the base station is increased. Depending on the required positioning accuracy, however, the acceptable distance may be more than a hundred kilometres. It is therefore not always feasible to have a dedicated base station for each site. If a base station is made available to several GNSS rovers at different sites, the correction data is typically transmitted over Ntrip. Code-differential correction data is also broadcast on marine radio beacon frequencies by base stations in many coastal areas, which may be utilized in some sites with a compatible receiver.

Due to the nature of ionospheric delay, it is possible to meet the performance of a local base station by estimating the local correction data based on several, more distant base stations. Several overlapping grids of base stations with various densities have been implemented worldwide: some publicly, others privately maintained. There are regional, nationwide, continental and worldwide grids that provide the differential correction service. The communication from the grid servers to the GNSS receiver can be implemented on Ntrip, over mobile network modems or via satellite. The differential corrections via satellite are broadcast one-way. Two-way communication over mobile networks, on the other hand, often includes transmitting the position of the rover to the server, typically in a NMEA 0183–compatible format. This makes it possible to optimize the differential corrections for the neighbourhood of the rover, resulting in improved accuracy. The satellite-broadcast corrections either leave the location-dependent ionospheric effect to be estimated by dual-band reception or provide a list of corrections for different areas of the grid. The area division does not necessarily follow the locations of the physical base stations. Publicly maintained coarse satellite-based augmentation systems (SBAS) can be utilized free of charge and are supported by most GNSS receivers, while sub-metre and more accurate services typically require a paid subscription and a receiver compatible with the particular service.

4.4.2 Odometry

Velocity measurements are often an essential part of pose estimation, producing uninterrupted high-bandwidth data. There are several sensor types for measuring either actual ground velocity or the angular velocities of the wheels. A ground speed radar can be used to measure the actual speed reliably in most conditions. A radar communicates over CAN or a V.24-based serial link, but pulse signal outputs are also common, being compatible with traditional wheel odometry sensors. A ground speed radar is, however, more expensive than wheel odometry sensors. Furthermore, a radar has to be mounted so that the conical beam towards the ground is entirely unobstructed. In some applications this is not possible considering the mechanical construction of the machines and protection of the radar. The simplest radar interfaces also output only the magnitude of the speed without indication of whether the machine is moving forwards or backwards. Visual odometry, on the other hand, may be used to estimate the velocity in six degrees of freedom (6DOF). The performance, however, depends on the texture of the site. Other aspects of implementing machine vision in mobile machinery applications are covered by a subchapter below.

Wheel odometry can be implemented cost efficiently and accurately, especially if the effect of wheel slippage can be taken into account in data fusion. Simple Hall effect sensors can be applied. Depending on the construction of the drive train and performance and reliability requirements, several sensors may be needed. If a toothed wheel and discrete Hall effect sensors are used, two sensors need to be mounted at a proper distance from each other to generate incremental signals for direction indication. In addition to using a separate toothed wheel, it is possible to choose various components of the drive train with internal sensors for measuring the angular velocity. The signal may be available over CAN, but typically the electrical interface is similar to having one or two discrete Hall effect sensors.

The number of pulses per wheel revolution depends on the accuracy requirement. For example, if one pulse per 2 cm of travel is generated, the frequency of the pulses is 500 Hz when travelling at 10 m/s. If the signal is measured with a conventional on-off input and processed in software, the input state has to be read at more than 1 kHz to detect every pulse. With a typical mobile PLC it is not possible to run user application at sub-millisecond intervals. A dedicated pulse frequency input is therefore required, also available in I/O modules. A quadrature input for incremental signals, however, is not as common as a simple frequency or pulse counter input. Moreover, several wheels may need to be measured. The measurement may need to adapt to both low and high angular velocities and therefore be able to not only count pulses but also measure cycle time. To improve data fusion accuracy, calculation may need to be synchronized with other measurements related to pose estimation. Thus, conventional mobile PLCs and I/O modules are sometimes insufficient for wheel odometry, especially when typical software development tools and default firmware are utilized.

4.4.3 Inertial measurements

To estimate the orientation of a machine and improve the location estimate, inertial measurements are applied. An inertial sensor is either an accelerometer for measuring linear acceleration or a gyroscope for measuring angular velocity. An IMU typically consists of several inertial sensors arranged at perpendicular axes, often both accelerometers and gyroscopes. Depending on the application, up to three perpendicular accelerometers and three perpendicular gyroscopes are needed. If several discrete inertial sensors are used, attention has to be paid to measurement synchronization, communication, mechanical alignment and calibration.

Although tactical-grade IMUs are sometimes used in research projects, they are expensive for mobile machinery applications. IMUs based on micro electrical mechanical systems (MEMS) are applied instead. There are devices with CAN communication, wide supply voltage range and protective enclosure, often targeted at automotive applications. Since automotive applications of MEMS IMUs are often related to drive stability control, the sensor configuration may be insufficient for pose estimation. While integrated mixed-signal circuitry makes these devices accurate and easy to calibrate, there are limitations in supported communication protocols and available output signals. Unless an IMU has sufficiently configurable real-time data processing, external processing is required. If the IMU has analogue outputs, a mobile I/O module or PLC can be used to measure the signals. In many cases, however, there are limitations related to conversion frequency, digital filtering, or real-time performance of networking. For optimal pose estimation performance, the inertial measurements must be accurately synchronized with other data.

4.5 Measuring configuration state

A machine typically has several controlled mechanisms, often actuated by hydraulic cylinders. The positions of these mechanisms need to be measured if closed-loop position control is required. Furthermore, the measurements may be needed to improve the accuracy of other sensors. In the case of a steering joint, the measurement can be used to improve pose estimation performance

[41]. In applications where sensors are mounted on a suspended rig, it may be feasible to measure the pose of the rig in relation to the machine frame.

Many mechanisms have a controlled joint angle. Sometimes it is possible to mount a rotary sensor directly on top of the joint. A machine, however, may have rather large gaps at joints allowing radial movement. This is not tolerated by a typical rotary sensor and protective arrangements are needed. Moreover, installation on top of a joint exposes the sensor to shocks, scraping and other mechanical stress. When designing the mechanical structure of an automated joint, a rotary sensor can be fitted inside the joint pin. In retrofit systems, this is typically not possible. It may be appropriate to locate the sensor away from the joint, instead. The rotary movement of the joint can be transmitted by a belt, for example. The orientation of a link can also be measured with inertial MEMS sensors. The key benefits of this approach include high mechanical endurance and the possibility to choose mounting location rather freely. On the other hand, sensor fusion of accelerometers and gyroscopes, and kinematic modelling of the mechanism are required to meet the performance of traditional solutions. [51]

Another option for determining the angle of a joint is to measure the distance between two points on the adjacent links. These points are often chosen near the brackets of the actuating hydraulic cylinder, providing protection to the sensor arrangement and simplifying calculation. A linear displacement sensor may even be integrated into the hydraulic cylinder, although in retrofit systems external sensors are common. Similar arrangements are needed when prismatic joints are measured. Cable actuated rotary sensors as well as sensors with a linear push rod are applied. Some sensor technologies are, however, not suitable for mobile machinery applications: the vibration of a machine heavily limits the life a conventional potentiometer, for example, if it causes the sliding contact to oscillate. With incremental sensors, on the other hand, the problem is that moving a mechanism for initializing the sensor is not always possible.

The sensors may be installed distant from PLCs and computers, on complex boom structures, for example. Therefore, the benefits of network communication in tolerance of interference and simple cabling are clear. If there are several sensors close to each other, analogue signalling and a networked I/O module may be applied. In many cases, however, it is feasible to choose a sensor with a suitable network interface. Regardless of the type of the sensor, mechanical protection has to be taken into account, considering both installation location and possible additional protective structures. Nevertheless, the sensor also has to be accessible for service with reasonable effort.

4.6 Laser scanning

Scanning lidars are common in robotics, providing accurate ranging to various surface materials. Typical applications include obstacle detection, pose estimation, and simultaneous localization and mapping. Some lidar models are targeted at outdoor and even automotive applications. These lidars have signal processing optimized for tolerating undesirable reflections from rain, snow and fog, for example. Furthermore, they often have an internal heater for operation at low ambient temperatures. There are, however, extra challenges when utilizing lidars in mobile machinery applications: When the heater is active, the power consumption of a lidar is increased heavily. The light emitted by a lidar is reflected by dense dust and smoke. It is, however, possible to decrease the effect by signal processing. [86] Nevertheless, a lidar should be mounted so that these obstructions are minimized during operation.

In mobile machinery applications, on-board lidar measurements are distorted by the movement of the machine, especially without accurate pose estimation. Even if the distortion can be cancelled, the movement of the machine makes a fixed single-plane lidar scan unintentional directions: entering or exiting a slope, for example, results in scanning too high or too low for reliable obstacle detection, as presented in Figure 19. There are several solutions to this problem, however. Several single-plane lidars may be aligned for improved coverage [42][72][105]. In this case, the measurements of each lidar should be synchronized or have accurate time stamps. A more integrated approach is to use a quad-plane lidar [12]. A single-plane lidar may be actively aimed by a controlled pod [15] or a more advanced gimbal with active stabilization [116]. It is even possible to extend the coverage of a single-plane lidar by continuous rotation [66] or oscillation [13][92]. If the lidar has no fixed mounting, the ranging data has to be synchronized with the actual orientation of the lidar. Integrated multi-plane lidars are also available for extended coverage. So far, the most extreme solution is a 64-plane scanning lidar [72][118]. Several of the listed solutions have external moving parts and rather limited operating conditions, which makes applying them to mobile machinery applications more difficult.

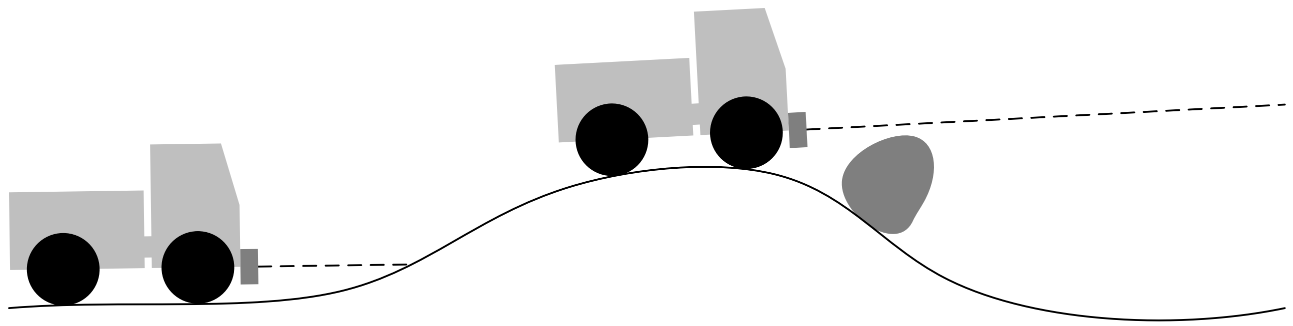

Figure 19. Challenges in obstacle detection with fixed single-plane lidar.

Most of the scanning lidars support Ethernet communication over internet protocol suite, typically UDP. It is therefore important to make sure that other communication does not cause significant delays, especially if the lidar data is used in sensor fusion. Communication over a V.24-based serial link is also common. If the data rate is low, the communication delay needs to be taken into account in calculation. Furthermore, each lidar may require a dedicated serial port. If the lidar has an active aiming system, the complexity of communication and functional integration is increased with additional sensors, actuators and controllers.

4.7 Cameras

Well implemented camera systems provide information for remote operation and monitoring. Furthermore, machine vision can be utilized in mobile machinery applications. There are cameras targeted at mobile machinery for reversing and work area monitoring, for example. For machine vision and remote operation, on the other hand, special arrangements are often required.

4.7.1 Machine vision

Typical cameras utilized in machine vision applications have high-performance image sensors and replaceable lenses for optimizing focus and framing, for example. The cameras typically communicate over IEEE 1394, Ethernet or USB. There are also digital interfaces targeted especially at machine vision and other video applications, such as Camera Link, CoaXPress and Serial Digital Interface (SDI). These specifications include higher layer protocol definitions, improving compatibility between camera models. On the other hand, these digital video interfaces require an adapter that is not included in embedded computers. There are also well-established higher level protocols for general-purpose interfaces, such as GigE Vision for Ethernet.

Depending on application, the timing accuracy requirement between cameras may be high. This is the case in depth perception by stereographic imaging, for example. In some cases, the accuracy achievable via software triggering is not sufficient. Many cameras support triggering by hardware inputs, and produce a strobe output for triggering a slave camera or an external flash. Unfortunately, these on-off inputs and outputs are implemented with various circuits and signal levels that typically require external circuitry between cameras for buffering and biasing. Industrial machine vision cameras are typically designed to have a regulated supply voltage and therefore require a DC/DC converter in mobile machinery applications.

Since regulating the lighting conditions in outdoor applications is not typically feasible, a camera has to adapt to dark and bright ambient lighting. For this purpose, auto iris lenses may be applied. Unfortunately, auto iris control is not common feature in machine vision cameras. To improve performance in dark conditions, infrared or visible lighting is also used. A camera with a high dynamic range image sensor may be utilized to improve detection of objects when there are both dark and bright areas in the field of view.

If a machine vision camera is used in a mobile machinery application, usually due to performance requirements, additional protection is mandatory for tolerating the operating conditions. An enclosure is often required for protection against dust and water. Moreover, heating may be required to maintain temperature and humidity within camera specifications and to keep the front window clear. The accumulation of dust and dirt on the front window has to be considered when selecting the installation location to maximize the cleaning interval. A mounting that attenuates mechanical shocks and vibration may be needed. A suspension, on the other hand, decreases performance as the camera is no longer aligned with the machine frame. In addition to protecting the camera, locking the mechanical adjustments of the lens has to be considered.

4.7.2 Remote operation

While automated functionality may rely on other perception sensors, a camera is often the most convenient solution for remote monitoring and teleoperation. Many of the requirements for a camera are, in this case, similar to machine vision applications. Image quality, however, may be lower in many cases as long as the camera adjusts to the expected lighting conditions and has a sufficient field of view. Another critical characteristic is a minimal transmission delay, especially in direct teleoperation. Some cameras with integrated digital encoding are therefore not fast enough for comfortable and safe remote operation.

The monitoring cameras that are targeted at mobile machinery applications can be applied to remote operation, which simplifies mechanical and electrical installation. However, these cameras typically output an analogue video signal. Although there are wireless transmitters for signals like this, it is typically feasible to utilize the digital wireless communications of the control system. For this, an Ethernet video server can be applied. There are automotive grade video servers for single or multiple cameras as well as analogue frame grabber boards for embedded computers. Although implementing the video server on an embedded computer among other functionality seems cost-efficient, the frame grabber expansion board may be more expensive than a standalone video server. It is also possible that running the video server application uses much of the computing performance. Moreover, the separate solution has better life-cycle manageability due to the limited driver support of embedded computer expansion boards.

Real-time video often consumes most of the available wireless data transfer capacity, especially if several on-board cameras are used simultaneously to cover the monitored area. Therefore, the specifications of video frame rate, resolution and encoding method need to be considered together with specifications for wireless communication. Alignment and synchronization of cameras is not as critical as with machine vision. However, if the image data of several cameras is fused into one video, these aspects need to be taken into account. A special case is stereoscopic video, where camera alignment and baseline are critical in producing a tolerable view for the remote operator. Although some of the alignment errors can be compensated by image processing, it results in increased delay and decreased image quality.

4.8 Emergency stop

Since an automated machine may be operated without an operator on board, there has to be a reliable wireless system for signalling emergency to the on-board control system to prevent accidents. The system has to be independent of the rest of the control system and rather simple considering verification and risk analysis. The safe reaction to the emergency signal depends on application. In this thesis, the discussion is limited to situations where stalling the engine and activating the brakes is considered safe. Depending on how a site or a machine is monitored, one or more handheld button units or a site-wide infrastructure may be needed. When testing new sensors and software with research machinery, an additional run/wait function makes testing more fluent. Moreover, an automated machine may be operated manually on-board for maintenance or transport. In these cases, operation without the wireless emergency stop system may be desired, which has to be taken into account in specification.

On a multi-machine site, an emergency stop may be global, machine specific or zone specific. The emergency stop system may implement one or more of these. The more emergency stop types are implemented, the more complex, and more difficult to verify, the emergency stop system becomes. The same applies to zone-specific emergency stop if a machine operates in more than one zone. Another challenge is posed if the number of simultaneously used button units in the system needs to be flexible.

There are commercial wireless emergency stop systems available. They are rather expensive and typically targeted at simple applications. Where these off-the-shelf systems are sufficient, they may still reduce the overall cost as less verification work is needed. However, customized I/O, software or communication protocols are often needed, which results in more complex verification. Whether the system is customized or off the shelf, using a dedicated radio channel is critical. If this aspect is neglected, other radio signals may block the emergency communication. If this occurs, the emergency stop system has to stop the monitored machines. These unintentional stops have to be minimized as they decrease productivity and, in extreme cases, may result in unauthorized bypassing of the emergency stop system.

Considering modularity, emergency stop systems have the benefit of being independent of the rest of the control system. This simplifies life-cycle manageability, in particular with solutions where the emergency stop system is implemented on a dedicated physical platform. I/O of the on-board unit has to be considered. The simpler interface the unit has, the more likely an off-the-shelf replacement system will be available. Nevertheless, when designing the on-board emergency stop circuit with commercial equipment, it has to be considered whether the control system needs to distinguish the emergency stop from an intentional shutdown.

4.9 Reference hardware architecture

A reference hardware architecture is presented in Figure 20, integrating the device types discussed in this chapter by utilizing the data transfer solutions presented in Figure 13. The low-level control system is distributed over CAN with CANopen protocol. CAN is preferred to Ethernet for better device availability in mobile machinery applications. CANopen, in particular, is chosen for flexibility, device availability, and standardized configuration management process. The data signalling rate of 1 Mb/s meets the data rate requirements listed in Table 1 since the cameras and lidars with high data rate are not part of the low-level control system. Another CAN is reserved for J1939 communication which is the industry standard interface in heavy duty diesel engines.

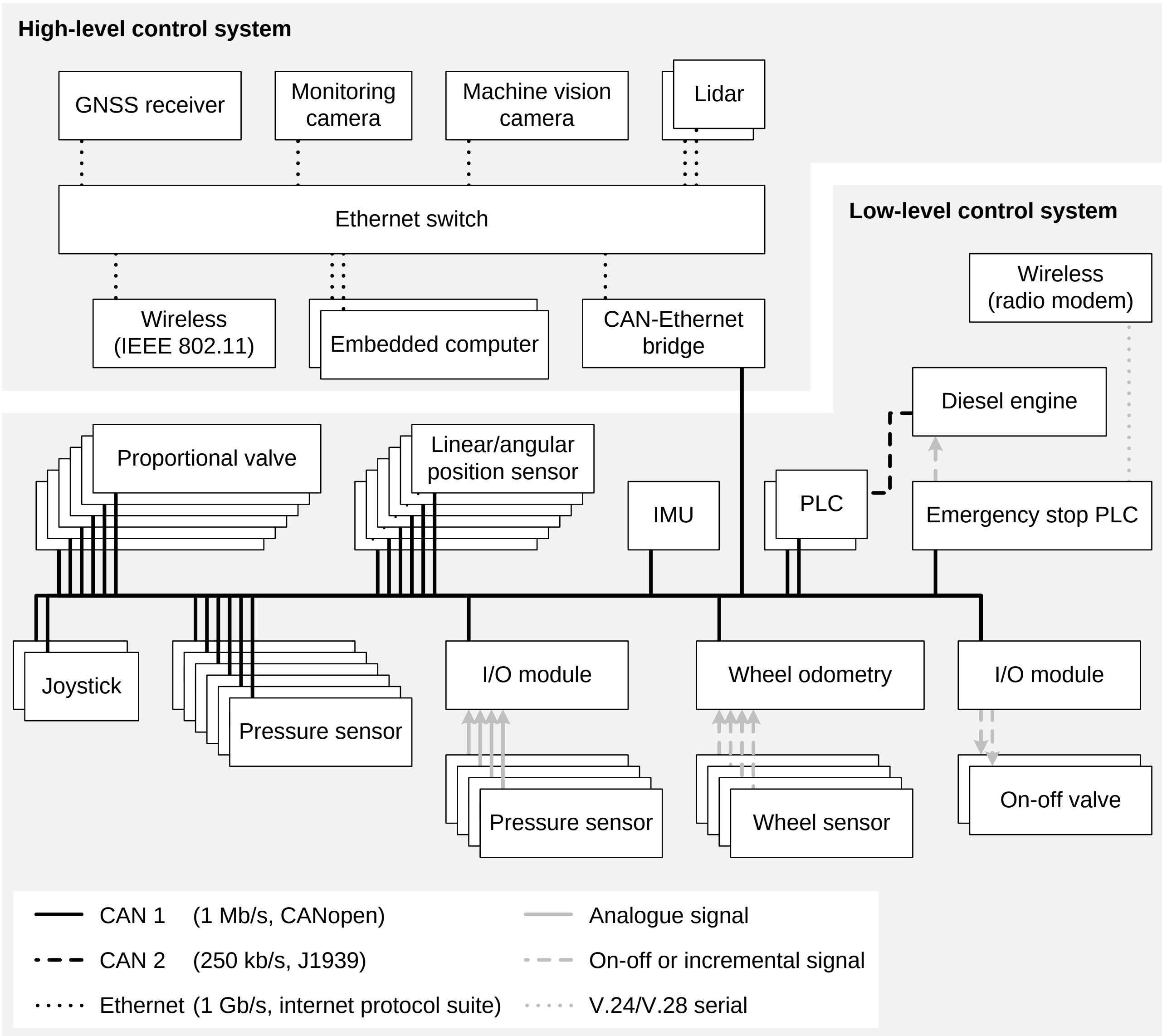

Figure 20. Reference hardware architecture.

In this reference hardware architecture, it is assumed that it is safe and sufficient to stall the diesel engine at emergency stop. The status of the emergency stop is, however, also signalled via CANopen. Joysticks, sensors, and hydraulic components with CANopen interface are applied. However, there are some exceptions: If a group of pressure sensors is installed into a manifold, it is feasible to choose sensors with analogue output and measure the signals with a CANopen I/O module located next to the manifold. The change in wire harness complexity is not significant. The communication becomes more efficient as several signals are transmitted in a single CAN message. The more sensors there are, the more cost-efficient this solution becomes since an analogue pressure sensor has lower cost than one with a CANopen interface. Because the CANopen interface generally increases the size of a pressure sensor, utilizing an analogue sensor is also feasible if the installation space for the pressure sensors is limited. Hydraulic on-off valves are also controlled by an I/O module because on-off valves with CANopen interface are not widely available.

A wheel odometry module and an IMU are placed in the low-level control system although they are pose estimation sensors for the high-level control system. This decision is made because the odometry data can also be applied in low-level speed control. To optimize the synchronization of the IMU and odometry data, they are connected to the same network. In addition, the installation locations of these sensors are close to the devices of the low-level control system. The sensor signals from four wheels are processed by the wheel odometry module before transmitting the odometry data over CAN. The odometry data of all wheels is thus synchronized and optimal odometry algorithms are applicable. Moreover, the steering angle signal is available on the same CAN from one of the CANopen position sensors and can be synchronized with the other pose estimation signals.

The high-level control system is distributed over Ethernet as proposed in Figure 13 since all the included device types are available with an Ethernet interface. To enable machine vision as defined in Table 1, 1000BASE-T is chosen. Conventional internet protocol suite is applied since camera and lidar protocols are typically based on UDP. The separate CAN-Ethernet bridge improves life-cycle manageability since neither an embedded computer with a CAN interface nor a mobile PLC with an Ethernet interface is required.

Utilizing CANopen, J1939 and Ethernet with internet protocol suite in the control system enables diverse future modifications and extensions: Replacement devices are widely available. Moreover, future automotive and industrial sensors, actuators, PLCs and embedded computers can be added by extending the original networks either directly or by standardized I/O modules. Connecting similar equipment to embedded computers through expansion boards would lead to higher dependency on software and driver support and board availability from a smaller number of vendors.

5 Generic embedded module

Since automated applications require new types of devices for sensing, actuation and communication, the devices have inputs, outputs or communication interfaces that cannot be connected to mobile PLCs or I/O modules. This applies to state-of-the-art technologies, in particular, but also devices that are not originally targeted at mobile machinery applications. Although some devices may be connected directly to an embedded computer, it is not feasible considering real-time performance or the aim for modularity and flexibility. The low-level control system of the reference hardware architecture presented in Figure 20 has three devices that involve these challenges: State-of-the-art inertial sensors or IMUs are not available with a CANopen interface. Optimal performance of wheel odometry requires a programmable device capable of sub-millisecond processing of four incremental sensor inputs. Emergency stop PLC needs to communicate through a radio modem. Implementing efficient half-duplex communication requires processing of a V.24/V.28 serial port at sub-millisecond accuracy.

In this chapter, the problems are approached by developing a generic microcontroller board with analogue and digital communication. With this board, CAN and serial port communications can be implemented and sensor-related data processing can be performed. Furthermore, it is possible to use the board for measurements and control with accurate timing. To utilize the microcontroller board in a control system, another board with simple application-specific circuitry and an enclosure with suitable connectors are applied. The design criteria, features and use of the boards are presented first. Then, practical experiences of applying the module are discussed. Although the main focus is on control systems of experimental machines, applicability to commercial machine control systems is also considered.

Commercially available boards with similar features are targeted at education, research and hobbyists. Therefore, a commercial solution may require several boards [40]. Typical evaluation boards of microcontroller manufacturers may have sufficient hardware included but the size of the boards is often too large for on-board applications. Moreover, the demanding operating conditions of mobile machinery are not considered in the design of these boards.

There are also commercial embedded modules with various protocol stacks based on CAN or Ethernet. These modules speed up the development of devices as there is no need to implement the software or circuitry related to the communication interface. Unfortunately, the modules may have limited software configurability and support only simple I/O interfaces to sensors and actuators. Therefore, in addition to the embedded communication module, a separate microcontroller is often needed to process application-related data or interface an embedded sensor. [17][81]

5.1 Board design

Design criteria for the microcontroller board were specified. Tolerating the operating conditions of mobile machinery was considered essential. Therefore, the operating temperature range of the board has to be at least from −20 °C to 85 °C. In addition, the board must have a robust mechanical structure that withstands shocks and vibration present in mobile machinery. In mobile machinery applications the board has to be protected against dust and water by aluminium or plastic enclosures with a degree of protection of at least IP55, as defined in Chapter 2.

The low-level control system of the reference hardware architecture presented in Figure 20 is distributed over CAN, which is a typical solution in automated mobile machines. Therefore, a CAN interface is mandatory. An asynchronous V.24/V.28 serial port is required for radio modem communication, for example. Ethernet connectivity would extend the applicability of the board but also make the board larger and more complex. An Ethernet interface is therefore considered optional. Furthermore; sensor, converter and driver ICs have synchronous serial interfaces. An SPI is therefore mandatory unless the performance of the microcontroller enables SPI implementation in software.

Many sensors are available only with analogue signal outputs. The microcontroller board must therefore have analogue voltage inputs. The input range has to be at least 0–2 V to avoid noise problems. Moreover, the input range must not exceed 0–5 V. It is then possible to measure the common voltage and current ranges without losing ADC resolution by choosing suitable external resistors. The ADC must have a resolution of at least 10 bits. Since the natural frequencies in mobile machinery are quite low, a conversion frequency of 10 kHz is considered sufficient. The board may also be used to produce control signals for actuators. Therefore, hardware-generated PWM outputs are mandatory unless the performance of the microcontroller enables PWM generation in software.

Applications include integrated digital circuits, different types of switches, indicators, relays and on-off valves. For these devices, general-purpose inputs and outputs (GPIO) are needed. Preferably, logic levels of both 3.3 V and 5 V should be supported. Some pins on a microcontroller package can usually be configured for two or more different functions. This flexibility must not be restricted by the design of the microcontroller board.

Since the board has to be universal and easy to use, it has to operate from a single positive voltage supply. Moreover, the connectors of the microcontroller board need to enable mating with simple application-specific boards, preferably even a stripboard or breadboard. The microcontroller board also has to include the minimum external components required by the microcontroller.

The microcontroller on the board has to perform at least simple digital filtering and other sensor-related data processing in real time. Simultaneously, the microcontroller has to be able to process CAN traffic up to 1 Mb/s at maximum bus load without losing messages. To meet the minimal functionality, there has to be at least 4 KB of non-volatile program memory and 512 bytes of RAM. Non-volatile data memory has to be available for storing at least 256 bytes of application parameters such as filter coefficients, scaling factors, and communication settings.

The software development tools have to include at least a C compiler, in-circuit debugging features and a programming interface. A well-established high-level development environment such as MATLAB/Simulink or an IEC 61131-3 compliant environment such as CODESYS would support life-cycle efficiency by minimizing hardware-dependency of the application software. The C compiler, however, is required when low-level I/O access and minimal processing overhead are needed. The tools have to be convenient to use, reasonably priced and reliable. The hardware of the programming interface has to be commonly used and available or at least easy to design and build.

5.1.1 Life-cycle manageability

Applying any microcontroller to mobile machine applications has challenges regarding different life cycles: The microcontroller ICs available at present are different from the ones that will be available one mobile-machine life cycle later. The software development tools for obsolete microcontrollers will not be supported. The compatibility of these legacy development tools with new operating systems, which also have shorter life cycles than mobile machinery, is therefore uncertain.

Since the life cycles in mobile machinery can be a lot longer than those of an operating system of a computer, the development tools must be actively supported and upgraded by the manufacturer. Considering the development tool support alone, it is important to assess the production prospects of different microcontroller models. Some development tools or development frameworks are available for several microcontroller models of different manufacturers. In this case, the possible future transition to another microcontroller model will be more straightforward considering software development and maintenance.

As stated above, the chosen microcontroller model will eventually become obsolete. Therefore, it has to be possible to re-design a pin-compatible microcontroller board using a new microcontroller. Most likely, it will not be a problem to find a microcontroller with similar or better computing performance. It is even possible to utilize a field-programmable gate array (FPGA) configured to operate as a microcontroller. With electrical characteristics of the microcontroller signals and types of the board connectors, however, the situation is not that simple. This has to be taken into account when deciding which signals of the microcontroller to make available and which board-to-board connectors to use. Long-term production prospects of connectors need to be assessed. In addition, complex microcontroller I/O without strong support prospects has to be avoided. In particular, this applies to I/O with unconventional electrical characteristics and the digital buses difficult to implement in software.

5.1.2 Microcontroller board

A microcontroller was selected based on the requirements and experience from different microcontroller families and manufacturers in machine control applications. A 56F8323 16-bit digital signal controller from Freescale Semiconductor was chosen. The core frequency of the microcontroller is 60 MHz. Its data arithmetic logic unit includes a multiply-accumulator unit for integer arithmetic. With pipelining, the microcontroller can perform a multiplication or multiply-accumulation of two 16-bit integers on every core clock cycle. [26] Although with a typical program the efficiency of the pipeline is not ideal, in many matrix operations the core architecture of the 56F8323 is efficient. This makes the microcontroller suitable for digital filtering, for example. The microcontroller does not have a floating point unit, however, which has to be taken into account in software development.

The features of the 56F8323 are presented in Figure 21. The microcontroller has a CAN controller, a 6-channel PWM controller, two 12-bit ADCs with 4 channels each, a quadrature decoder for incremental pulse signals, two logic level serial ports and two SPIs. Any of these, apart from the ADC inputs, can be disabled and the corresponding pins can then be configured for GPIO. The microcontroller also has an input for external interrupts. The 56F8323 has a supply voltage of 3.3 V but its logic-level inputs tolerate more than 5 V. Logic-level outputs tolerate external pull-up to 5 V. [2]

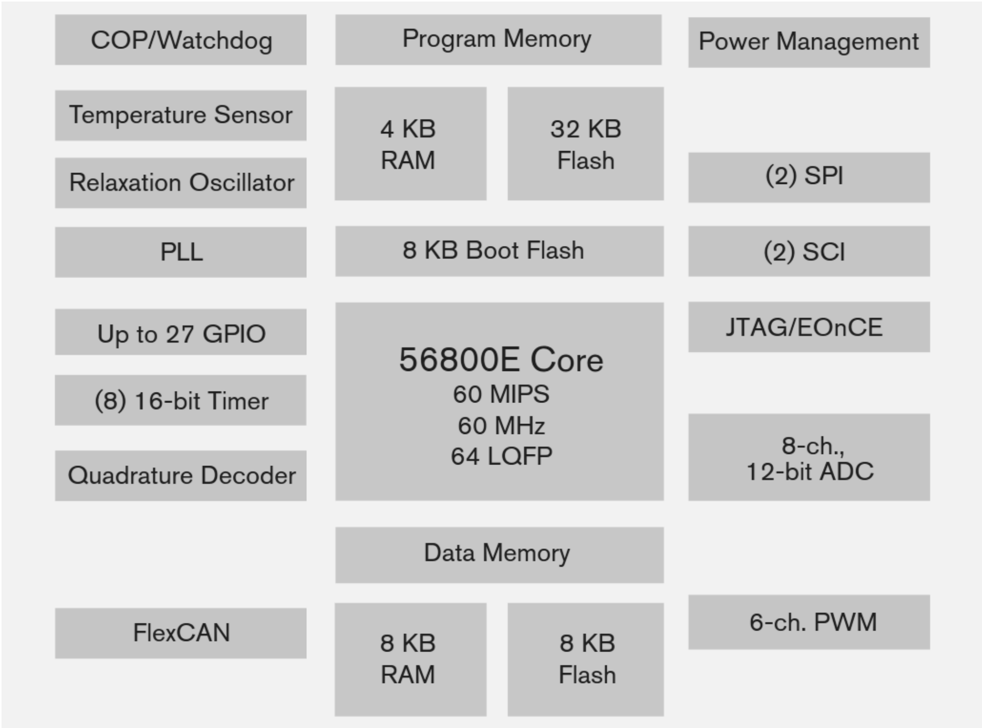

Figure 21. Features of a 56F8323 microcontroller. [3]

For flexibility and easy prototyping, the board was planned to fit a normal dual inline package (DIP) socket. The 40-pin variant would have been optimal regarding the number of pins. The available board space, however, was insufficient. Moreover, an option for a more secure fastening was considered necessary. Therefore, the row spacing of the pins was designed to be 25.4 mm instead of the 15.2 mm of the DIP specification [19]. A mating socket can be made of two separate 20-pin single inline package (SIP) sockets. For single prototype applications, it is also possible to split a 40-pin DIP socket. 2.5 mm holes were added to the corners of the board for additional fastening. The outline of the board was designed to be 30 mm by 60 mm. An assembled, industrially produced board is shown in Figure 22.

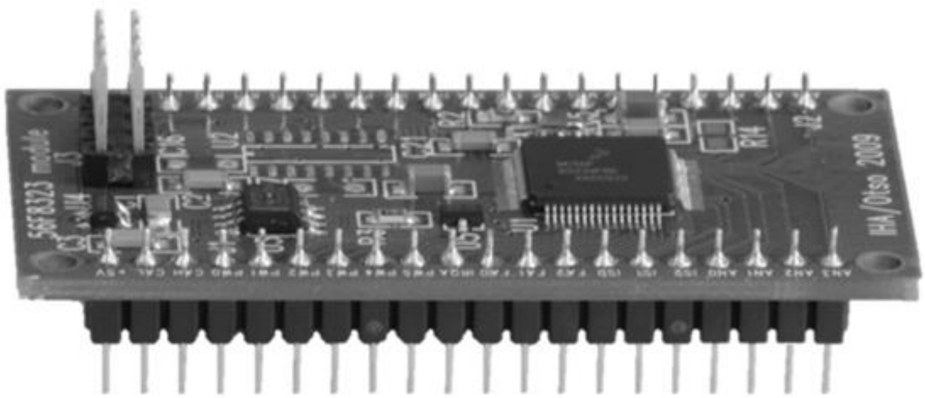

Figure 22. An assembled microcontroller board.

A block diagram of the microcontroller board is presented in Figure 23. Since the microcontroller operates from a power supply of 3.3 V but other circuitry on the board requires 5 V, the power supply of the microcontroller is generated with a linear regulator. A voltage supervisory circuit holds the microcontroller in reset state if the regulated voltage drops below normal range.

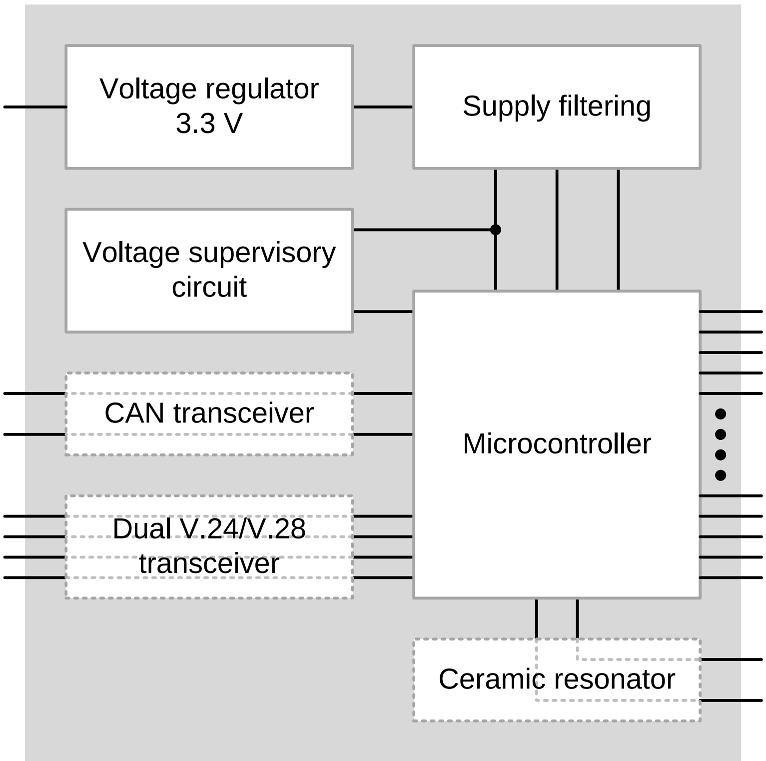

Figure 23. Block diagram of microcontroller board.

CAN and V.24/V.28 communication were considered essential in several applications. Therefore, transceivers for these interfaces were included in the microcontroller board. The 56F8323 includes an on-chip relaxation oscillator which can be used to generate the system clock. The accuracy of the internal relaxation oscillator, however, does not meet the requirements of CAN protocols that specify a late sampling point for maximum bus length (CANopen and J1939, for example). Some applications also require more accurate timing. Therefore, an external frequency reference can be used. Because of size optimization, a high-accuracy ceramic resonator was preferred to quartz crystal.

To maximize available GPIO, both transceivers and the ceramic resonator can be left out if they are not used. Solder pads for zero-ohm resistors were included for bypassing the omitted transceivers. Since the 56F8323 has only well-established digital interfaces, PWM outputs, GPIO, and analogue voltage inputs, all vacant signal pins of the microcontroller were connected directly to the board-to-board connectors, as illustrated in Figure 23.

The microcontroller has an IEEE 1149.1–compliant interface for programming and in-circuit debugging. The interface is commonly referred to as JTAG according to the original developer, Joint Action Test Group. An Enhanced On-Chip Emulation (EOnCE) module that can be accessed through JTAG is included in the microcontroller for debugging in real time. An 8-pin header is placed on the microcontroller board for accessing the JTAG/EOnCE interface. Software development is done with CodeWarrior development tools. The latest versions are based on the Eclipse open development platform, which has also been adopted by several other microcontroller manufacturers.

5.1.3 Application-specific board

Using the microcontroller board in a control system requires another board which has at least a power supply and wire terminals. Depending on the application, the motherboards can include different components. In this thesis, these motherboards are referred to as application-specific boards. A key benefit of having a separate microcontroller board is that the application-specific board can be simple.

In most cases, the electric power supply is the battery and alternator of the machine. Therefore, the application-specific board typically includes a regulated power supply that tolerates battery voltage at input and outputs 5 V to the microcontroller board, at least. The application-specific board may also have components that require a regulated 5 V power supply. If the power consumption of these components is less than 200 mW and the machine has a 12 V battery, the power supply can be a conventional linear voltage regulator. Otherwise, a switched-mode voltage regulator has to be used or special care taken to ensure proper heat dissipation.

Minimum configuration also includes a socket for the microcontroller board and wire terminals for the power supply and desired signals. The application-specific board is shaped and drilled so that it can be fixed into an enclosure. A typical arrangement with an enclosure and a panel connector is shown in Figure 24. If the number of components is small and none of them are surface-mount devices, the application-specific board can be made using stripboard.

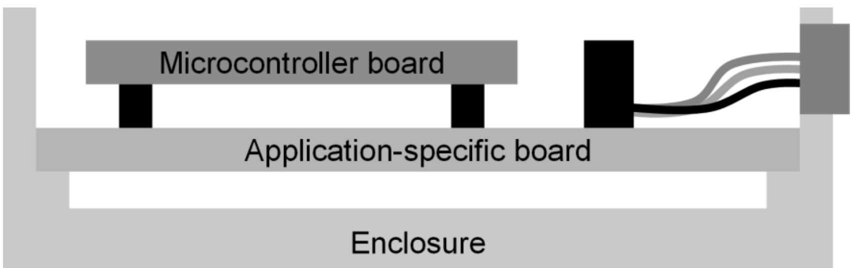

Figure 24. A typical arrangement with an application-specific board.

Since the microcontroller board has only logic level inputs, an application-specific board has protective or biasing input circuitry. Analogue inputs may also have amplifiers and external filtering circuitry. Logic level outputs may control power driving transistors. An application-specific board may also include board-mounted embedded sensors, transceivers, converters or mass-storage devices.

5.2 Discussion

The microcontroller board has proven to suit research applications, which is demonstrated by several applications presented in Chapter 6 and Chapter 7. The effort required in implementing an application has been reasonable: devices with simple I/O have been designed, built into protective enclosures and programmed, all by one person in less than one week. Utilizing the microcontroller board has made application-specific boards simple to design and quick and easy to build. The software development with CodeWarrior has also been efficient, due to reusing source code and utilizing the integrated Processor Expert tools, including automatic code generation. The automatically generated code, however, sometimes requires manual corrections. Since the microcontroller software is written in C, it can also be ported to other microcontrollers.

Updating the software of a microcontroller board requires connecting a programming cable to the JTAG header of the board. Because the devices are sometimes installed in hard-to-reach locations, software updates via CAN would be useful. This would require programming a small CAN bootloader firmware in all the microcontrollers. The extra effort would, however, make updating more comfortable and save time in the long run. On the other hand, efficient in-circuit debugging would probably not be possible over CAN. It is also possible to update the software by replacing the entire microcontroller board with one containing the new software.

The dimensions of the microcontroller board have been small enough for all the applications. The minimum enclosure size is typically limited by the panel connectors required to maintain the minimum degree of protection specified in Chapter 2. Therefore, there has been no need to choose a larger enclosure because of the microcontroller board.

A compatible board can be designed using future microcontrollers. New microcontrollers tend to require less and less board area. On the other hand, for pin compatibility, it may become necessary to re-design the board also for a larger device. However, by using four-layer board and surface-mount pin rows, the microcontroller IC can cover a much larger area than the 56F8323.

Because the board suits diverse applications, it was feasible to have a batch of them industrially produced. Therefore, the electronic components on the microcontroller boards are correctly placed and soldered. Probably due to the industrial production, the microcontroller board has proven to be reliable.

Although all the applications of the microcontroller board have been related to academic research, a similar approach could also make commercial control system development more efficient. A similar microcontroller board could be used in prototyping new sensors, for example. The microcontroller family chosen in this case is also quite popular in commercial machine control and measurement modules.

Many of the research applications where the microcontroller board has been applied could have been implemented with small commercial microcontroller modules. Most of these modules do not, however, include a CAN controller. An Arduino module with the CAN shield [40] would have been a possible solution, although larger, more expensive and possibly mechanically less reliable. On the other hand, the variety of expansion boards (shields) makes the Arduino a good option. In some of the applications, a product like the CANopen Chip F40 [17] could have been used, but for most cases, the fixed software would have been a problem.

6 Case 1: Automated wheel loader

An automated wheel loader with a flexible electronic control system was developed to be used as a generic research platform. In this chapter, the design and implementation of the electronic control system are presented. Research applications utilizing the machine and meeting the requirements of modularity, flexibility and robustness are discussed.

The machine is used in research and demonstration of automated path following, short-range remote control and digital working hydraulics [9]. The control system also needs to support operation as a member of a fleet of automated machines. In addition, different optimizations of the power train control are to be researched with the wheel loader. Moreover, the control system has to support modifications of the hydraulic system. Overall, the control system has to be flexible in terms of updating control algorithms and adding or replacing devices.

6.1 Mechanical construction

Although the frame of the machine is from a commercial loader, the engine and the hydraulic system have been replaced. The machine has a mass of 3500 kg, a 100 kW common rail diesel engine and AFS with two hydraulic cylinders. Since pure drive-by-wire is needed, the steering cylinders are controlled by an electrically actuated proportional valve. The front attachment can be changed. Most of the tests and demonstrations have been conducted with a pallet fork installed, as shown in Figure 25.

The machine has a closed-loop hydrostatic transmission with a variable-displacement pump and four parallel fixed-displacement hub motors. The working hydraulics circuit has been implemented with digital hydraulics. There are 20 seat type on-off valves for both lift and tilt, 5 in parallel for each control edge. [9]

Figure 25. Automated wheel loader.

6.2 Control system architecture

For robustness, flexibility and product range, CAN with CANopen was chosen as the main network technology. To enable future extensions with sensors and multiple embedded computers communicating at high data rates, Ethernet with internet protocol suite was also included. Furthermore, on-board Ethernet makes it possible to utilize well-established wireless standalone solutions. In addition, CAN with SAE J1939 and V.24/V.28-compatible serial communication with navigation-related protocols were applied where neither CANopen nor Ethernet were available.

The layout of the control system is presented in Figure 26. The devices are divided into three levels based on function. The bottom level in the diagram consists of sensors and actuators, and possible sensor or actuator specific real-time signal processing. In addition, a joystick, a display and modules for wireless communication are considered to be on the bottom level. The middle level includes the hardware for real-time control of steering, velocity and working hydraulics. The target values for the middle level are generated either directly by the on-board or remote operator over the equipment on the bottom level, or by the embedded computer for automated functionality on the top level of the diagram.

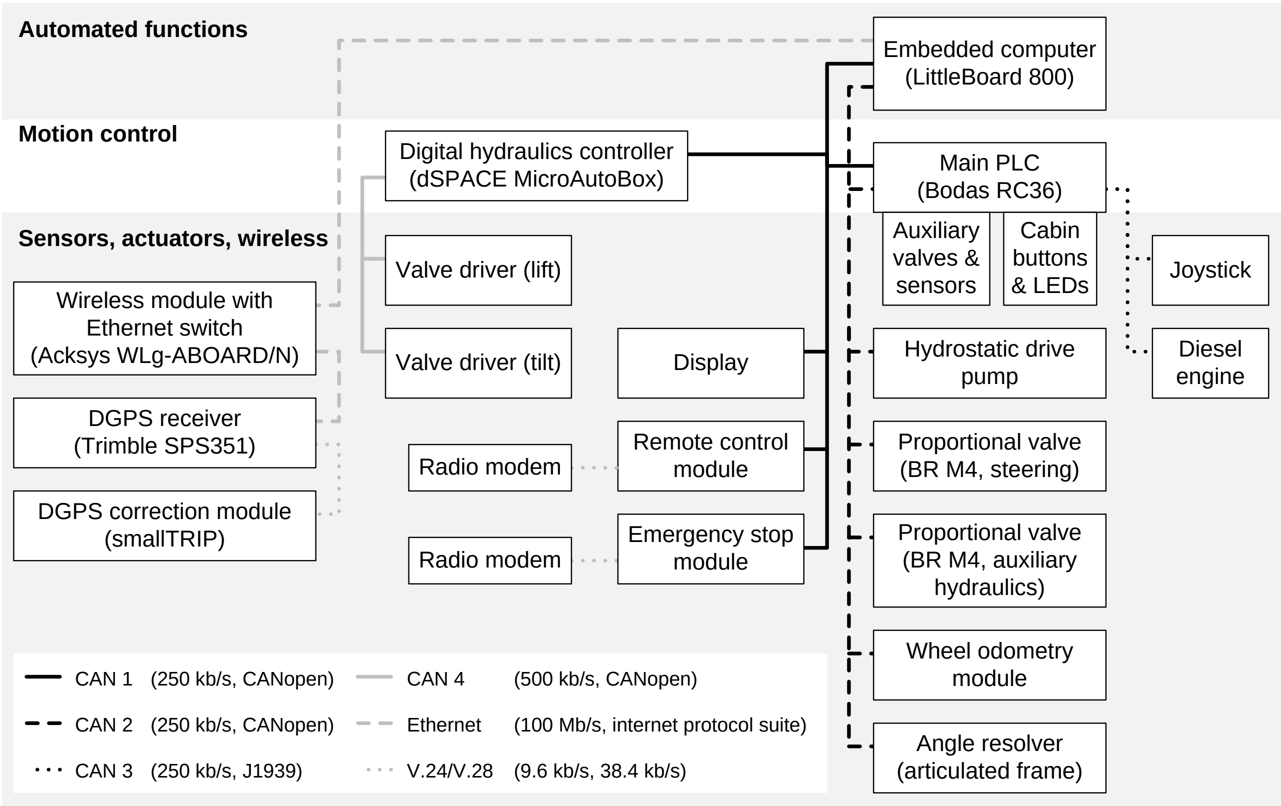

Figure 26. Control system layout.

As many components of the hydraulic system as possible were chosen to have integrated electronics with a CANopen interface. The CAN devices are grouped into four buses. Since the only SAE J1939 devices are the diesel engine and the joystick, they are connected to the same bus. The CANopen devices are divided into three buses based mainly on device functionality to balance the bus loads.

Some of the CANopen devices are designed, built and programmed at the department since no applicable commercial products are available. These include the digital hydraulic valve drivers and the modules for remote control, emergency stop and wheel odometry. All of these deploy the generic embedded module presented in Chapter 5.

6.3 Main PLC

The main mobile PLC of the control system was specified to have several CAN interfaces and versatile I/O for conventional hydraulic valves, analogue current and voltage signals and switches. Moreover, extra I/O was considered essential for convenient future testing of sensors and actuators. For further flexibility, data processing performance was targeted to be high among the conventional mobile PLCs. Standardized or well-established software development tools were also required.

BODAS RC36-20/30 from Bosch Rexroth was considered to meet the specifications. The PLC has four CAN interfaces, several analogue voltage and current inputs, on-off inputs, frequency inputs, and outputs for proportional and on-off valves. The microprocessor core has a multiply-accumulator unit and an FPU. The clock frequency of the core is 150 MHz and most arithmetic instructions can be repeated at least every third core clock cycle. Software development can be done with BODAS-design, which is based on CODESYS tools and is IEC 61131-3 compliant. Furthermore, C development tools are available in case the flexibility or performance of BODAS-design is not sufficient for an application. Since the PLC is targeted at mobile machinery applications, the issues related to mechanical and electrical robustness are minimized.

In addition to CAN communication, the PLC is used to measure analogue signals from pressure and temperature transducers, and control the pump of the working hydraulics via an electrically actuated proportional pressure relief valve. Auxiliary functions of the PLC include parking brake and front attachment lock control. The PLC performs power management, velocity and steering control, and data routing to the embedded computer for automated functionality.

6.4 Power train and steering

To meet the velocity and traction performance of commercial machinery with similar structure, the diesel engine was required to have a maximum power output of 100 kW. For convenient electrical control and modularity, a CAN interface was preferred for setting target engine speed. Hydrostatic transmission with an electrically controlled variable-displacement pump and four hub motors was considered a suitable generic solution for testing different control strategies and hydraulic circuits. For steer-by-wire functionality, an electrically actuated mobile proportional valve was specified to control the AFS cylinders. To simplify control system layout and increase modularity, hydraulic components with CANopen interface were preferred.

A 44 CWA diesel engine from Agco Power was selected. The engine has a SAE J1939 interface for control over CAN. There is also a dedicated on-off input for enabling and stalling the engine. The engine complies with Stage III A and Tier 3 emission requirements. A variable-displacement pump from A4VG-series by Bosch Rexroth was selected. The pump has an internal proportional valve for displacement control. The control valve is electrically actuated and controlled by integrated electronics. There is a CANopen compatible interface for setting the target displacement and other parameters as well as reading diagnostic data including signals of internal sensors. A dedicated on-off input can be used to set the pump at zero displacement in case of emergency.

Hub motors from MCR5-series by Bosch Rexroth were selected. The motors have a parking brake, a reduced-displacement mode and two Hall effect sensors generating an incremental output for measuring angular velocity. The parking brake and reduced-displacement mode are hydraulically actuated and controlled by external on-off valves. These valves are controlled by the main PLC.

A sandwich type mobile proportional valve from M4-series by Bosch Rexroth was selected for steering and auxiliary hydraulics control. Both spools of the valve have integrated control electronics with a CANopen interface. In addition, there are on-off safety valves for enabling the main spools. The coils of the safety valves are directly controlled by the main PLC. A pin-shaped angular resolver was fitted inside the AFS joint to enable closed-loop steering control. The resolver has a CANopen interface.

6.5 Digital hydraulic boom and bucket control

One of the topics to be researched with the wheel loader is applying digital hydraulics to mobile machinery. There are four digital flow control units (DFCU) controlling the lift cylinder and another four controlling the tilt cylinder. Each DFCU consists of five parallel on-off valves with different orifice sizes. Therefore, each DFCU has 31 nonzero states resulting in practically proportional volume flow control. For electronic pressure compensation, advanced operating modes and test measurements, pressure sensors were included in all actuator ports. Supply pressure was also measured. [52]

To minimize unwanted pressure transients during state transitions, the closing and opening times of the on-off valves have to be accurately synchronized. This can be achieved with special valve driver circuitry. [77] Since the working hydraulics circuit requires 20 special on-off outputs, no commercial valve driver was available. A 20-channel valve driver was designed and connected to CAN with the generic embedded module. 20 logic-level outputs from the microcontroller board were used to control the on-off output circuits. Pressure sensor signals were also measured by the microcontroller board. To have enough logic-level outputs, the serial transceiver was left out. The microcontroller was programmed to transmit pressure values and read valve control patterns via CAN.

In addition to the main PLC, the middle level of the control system has a separate controller for controlling the digital working hydraulics. Because complex experimental control algorithms were to be tested, dSPACE MicroAutoBox hardware was selected. The dSPACE MicroAutoBox is targeted at control system prototyping in automotive applications. The research-oriented MATLAB/Simulink environment can be directly used to develop the control algorithms. Moreover, it is possible to monitor the controller, log data and adjust parameters online. To enable automated loading and other sophisticated control functions, potentiometers were installed to measure the lift and tilt angles of the working hydraulics. These analogue sensors were connected directly to the ADC inputs of the MicroAutoBox. Two separate CAN interfaces of the MicroAutoBox are utilized: one for communication with the valve drivers, another for communication with the main PLC.

6.6 Computing automated functions

Although it is possible to utilize the MicroAutoBox in automated functionality research to a certain extent, a separate embedded computer was considered superior in flexibility and cost-effectiveness. CAN and Ethernet communications were specified to be mandatory. To enable new interfaces to be added, a well-established mechanically robust bus for embedded expansion boards was seen as valuable. MATLAB/Simulink with xPC Target was considered an optimal development platform for real-time software for the first research projects and demonstrations. Therefore, the embedded computer and its expansion boards were required to be supported by xPC Target. Based on experience of xPC Target in a laboratory environment, a single-core Pentium processor operating at over 1 GHz clock frequency and with 2 MB of L2 cache was considered to have sufficient performance for the first path-following application.

A Pentium M–based LittleBoard 800 with a 1.4 GHz clock frequency was selected. The chosen model can be operated without a cooling fan over a wide range of ambient temperatures. The computer complies with Embedded Board, eXpandable (EBX) specification [29] with a PC/104-Plus expansion bus. There are two Ethernet interfaces, one of them implemented with a controller supported by the xPC Target. A PC/104 expansion board with two CAN interfaces was installed. Unfortunately, very few CAN expansion boards are supported by the xPC Target. A PCAN-PC/104 from PEAK-System Technik was chosen due to previous experience in developing an xPC Target driver for an expansion board from the same product series. Since the source code of Linux drivers was available and the board is based on widely used CAN controller ICs, the extra effort required by the driver development was reasonable.

The LittleBoard 800 can be powered from a regulated 5 V supply. Depending on the boards installed in the PC/104-Plus bus, additional regulated supply voltages may be required. Fortunately, the same 5 V power supply is sufficient for the PCAN-PC/104. A DC/DC converter with a wide input voltage range was installed inside the same enclosure with the computer. M12 panel connectors for Ethernet and the two CANs were also installed on the enclosure. Another M12 connector was included for accessing BIOS through a V.24/V.28 serial port. Moreover, the serial port can be used to connect various embedded sensors to be tested on-board. The computer has a parallel ATA controller for conventional hard drives and SSDs. In addition, USB mass storage or a CompactFlash memory card may be utilized. Any of these can be used as a system drive. Since neither the xPC Target real-time kernel nor the application requires writing on the system drive, an industrial grade CompactFlash memory card was chosen.

Since the real-time kernel for standalone xPC Target models has to be invoked from an MS-DOS compatible operating system, FreeDOS was installed on the CompactFlash card. The standalone xPC Target models can also be stored on this system drive. Although it is possible to invoke the real-time kernel and specify a standalone model file at FreeDOS command line, it is more convenient to have the model started as soon as the operating system has booted, without any manual action. However, changing which model file is run requires modifying a batch file on the system drive. This, in addition to managing the model files on the system drive, is not possible once the xPC Target real-time kernel has been invoked.

Since there is no consistent support for remote access and networking in MS-DOS compatible systems, it was considered most convenient to utilize live USB with GNU/Linux for remote accessing of the CompactFlash. To enable live USB, the boot sequence of the BIOS was set to give the first priority to USB drives, before the CompactFlash. A panel connector for USB with sufficient protection was installed on the enclosure. A mating cable was fitted with a panel feed-through on the dashboard for easy access. In addition to enabling live USB, this arrangement makes it possible to run an alternative xPC Target model from a USB drive.

For development and testing of xPC Target models, the real-time kernel may run a loader model, enabling the application models to be loaded from a host laptop. Since the loader model supports communication over Ethernet utilizing internet protocol suite, it is possible to have the host laptop connected on-board or over the site-wide wireless network.

6.7 Pose estimation sensors

One of the first applications to be demonstrated with the wheel loader was specified to be automated path following. Horizontal position error was specified to be less than 0.5 m most of the time to be able to follow a typical road and perform reasonably in various earthmoving tasks, for example. Demonstrations were planned to be conducted at various closed locations without other traffic or dynamic obstacles. The setup work at a new site was to be minimized. The sites were assumed to be rather flat, possibly without any landmarks, and mostly have a line of sight to navigation satellites. Therefore, a GNSS receiver and wheel odometry, possibly with inertial measurements, were considered to be a sufficient sensor combination. Since there is no sensor for solving the initial orientation of the machine, a short path has to be driven to enable orientation estimation from successive position estimates.

6.7.1 GNSS receiver

Based on the accuracy requirement, a code-differential receiver was considered sufficient. An interface for various external sources of correction data was required. A Trimble SPS351 differential GPS (DGPS) receiver with a Trimble GA530 antenna was selected. In addition to receiving GPS satellite signals, SBAS correction data is also received. This includes the European Geostationary Navigation Overlay Service (EGNOS). Furthermore, the receiver and the antenna are compatible with the correction data transmitted on marine radio beacon frequencies. The receiver and antenna are targeted at marine applications in demanding environmental conditions. Therefore, no additional protection is required. The receiver has diverse options for communication. Internet protocol suite over Ethernet was chosen for transmitting the position data to the embedded computer since processing the UDP packets is straightforward within the xPC Target models. Moreover, the on-board Ethernet switch had a spare port, making the hardware installation straightforward.

Initial tests showed that although there was a marine beacon transmitter located at a distance of 125 km, its signal could not be received reliably. To make the machine independent of the working site, a commercial grid-based correction service (Trimble VRS DGPS) was selected. The position data of the DGPS receiver is transmitted to the Ntrip server over mobile Internet every 10 seconds. An optimal set of correction data for the current working area is then received from the server every second. For this communication, an embedded mobile Internet module with Ntrip client functionality was installed. The module has a V.24/V.28 compliant serial port for communication with the DGPS receiver. The receiver outputs position data according to NMEA 0183 and receives the correction data according to the RTCM specification. The DGPS receiver also has Ntrip client functionality. This, however, requires that there is Internet access from the on-board Ethernet. Utilizing the separate module as the Ntrip client enables correction data to be received almost anywhere without on-site wireless Internet access. Moreover, with the external module it is possible to keep the embedded computer and the DGPS receiver entirely separated from the Internet for improved security. The module can also be used as a modem for receiving the correction data through a traditional circuit-switched connection.

6.7.2 Wheel odometry

Since the applications of the wheel loader include power train optimization and testing different pose estimation arrangements, it was considered necessary to measure the angular velocities of all the wheels. An encoder was installed on each wheel, outputting incremental signals. The velocities of 0–40 km/h with direction indication were to be measured at maximal accuracy over the velocity range, synchronized with the AFS angle measurement. Therefore, a special odometry algorithm and real-time input processing were needed.

A simple application-specific board was designed to be used with the generic embedded module. Only a power supply and voltage dividers with transient protection to adapt the sensor signals to the logic-level inputs of the microcontroller board were included on the board. The microcontroller was programmed to read the inputs every 500 μs and continuously calculate the angular velocity of each wheel, then transmit the result via CAN when requested by the higher level controller. The request is done by transmitting a SYNC message as described in CANopen specification [16].

6.8 Short-range remote control

Remote control of mobile machines is one of the research topics tested and demonstrated with the wheel loader. For flexibility, a general-purpose radio modem link is used. A compatible handheld remote control and communication protocol are presented by Uusisalo [121, pp. 42–57]. Although mobile PLCs and I/O modules are available with a serial port, accessing the registers of the serial port from the control application in real time is typically not convenient. Therefore, a CANopen compatible remote control interface was designed utilizing the generic embedded module. Another benefit is that remote control functionality can then be added to other machines by installing similar devices.

In this case, both CAN and serial port transceivers were mounted on the microcontroller board. The application-specific board consisted of power supply for the microcontroller board, another power supply for the short-range radio modem, and connectors. The software reads data from the serial port every 200 µs, transmits a response packet after a complete control packet is received, and transmits the control values via CAN. The response to the remote controller can include force feedback data in addition to conventional status information.

6.9 Site-wide wireless communication

A separate general-purpose IEEE 802.11 compliant wireless module with Ethernet interface was selected for secure high-performance wireless communication. A standalone module was preferred since it is independent of the operating system of the embedded computer. Moreover, replacing the wireless solution in future is straightforward. The module is targeted at vehicle applications. Therefore, neither electrical nor mechanical installation requires extra arrangements. The wireless module includes a 2-port Ethernet switch with M12 connectors. Therefore, no additional switch is required with the current equipment. The ports were connected to the embedded computer and the DGPS receiver as presented in Figure 26.

The networking configuration was performed via a web browser interface quickly and easily. The wireless module was configured to act as a wireless client, establishing an encrypted connection to the on-site wireless network. The network has no Internet access, simplifying security issues. Instead of a wireless client, the wireless module can be configured to operate as an AP. This removes the need for fixed on-site wireless infrastructure in simple applications.

6.10 Emergency stop

Automated travel tests were planned to be conducted without an operator on board. Therefore, a system with a dedicated wireless link was designed for independent emergency stop functionality. The system was designed utilizing the generic embedded module to make the devices small and convenient to update. The generic embedded module is used in two different modules: a relay module and a button module. The relay module is installed on the machine, controlling the emergency stop signal that disables the outputs of the main PLC, stalls the engine and activates the brakes. The handheld button module consists of the microcontroller board, an application-specific board with button inputs, a battery pack and a robust radio modem.

The application-specific board of the relay module is similar to the one in the remote control module. In addition, the board has a transistor that drives the emergency stop relay that is in series with the conventional emergency stop buttons of the machine. There is also an input for a bypass switch, which disables the wireless emergency stop. The actual switch has two pairs of contacts. One pair is used to bypass the relay. The other pair signals the microcontroller board if the bypass is enabled.

The emergency stop button in the button module is also a double-pole switch. While one pair of contacts shuts off the power supply to the microcontroller and the radio modem, the other signals the emergency stop to the microcontroller board. In the button module, the application-specific board has an electrolytic capacitor that powers the button module for approximately 200 ms after the emergency stop button has been pressed. After initial tests, it was noted that an additional run/wait function would streamline testing. Therefore, another button with momentary action was installed. In addition to the button inputs, the board has a voltage regulator, a connector for the radio modem and outputs for LED indicators.

The software of the relay module transmits a repeating bit pattern to the button unit. If the button unit does not reply with a correctly manipulated pattern within the period of the microcontroller watchdog, the relay is de-energized, resulting in an emergency stop. The states of the emergency stop button and the run/wait button are transmitted in the response packet from the button module. When the emergency stop button is pressed, the energy stored in the shutdown capacitor is sufficient for transmitting two or three response packets. Therefore, the relay module can trigger the emergency stop before watchdog time-out. The status of the emergency stop, the run/wait button and the bypass switch are transmitted over CAN to the main control system. The status of the bypass switch is also transmitted to the button module to be shown with the LEDs.

The radio modem communication is synchronized to packets transmitted by the button module. The communication protocol supports a system of up to two relay modules. There are two time-slots for the relay modules after the button module has completed its transmission. Therefore, both relay modules have an individual delay before starting their transmission. The protocol could be extended to three machines without notable delay. However, if the number of machines is increased, it is likely that several supervisors and several button modules are required, leading to fundamental modifications of the emergency stop system.

6.11 Electrical power supply

Almost all the devices of the electrical system have a range of supply voltage compatible with a 24 V battery system. It was also estimated that a 24 V system is more likely to be supported by the equipment to be installed in future projects than a 12 V system. Since the electrical system of a research machine is frequently operated without the engine running, a starter battery type that tolerates deep discharge was selected. Two 12 V batteries were connected in series, resulting in a 24 V system with a capacity of 75 Ah, sufficient to power the electrical system for several hours without the engine running.

A 28 V alternator with a nominal output current of 60 A at 6000 rpm had been mounted on the engine for prior tests. The transmission ratio between the alternator and the engine is 2.6. Therefore, the alternator is rotating at 2600 rpm when the engine is idling at 1000 rpm. The maximum output current of the alternator at 2600 rpm is approximately 38 A. The maximum continuous consumption of the electrical loads without actuating any hydraulic valves is estimated in Table 3, assuming the alternator output voltage is 28 V. Therefore, the total of 360 W corresponds to 13 A. This indicates that at least 66 % of the alternator output is always available for charging the batteries when the engine is idling. It has to be noted, however, that unlike a typical machine, the wheel loader has no lights. A commercial equivalent of the machine has work lights and headlights rated at 330 W in total.

Only the embedded module used as the Ntrip client requires a 12 V power supply. Since no optional devices were easily available, a small DC/DC converter was needed. A 20 W model was selected, having 13 W of extra capacity over the consumption of the embedded module. The converter was installed into a protective enclosure with M12 connectors, enabling the converter to be used with possible future low-power devices requiring a 12 V power supply. It was, however, noted in initial tests that the linear voltage regulators of the remote control module and the emergency stop relay module overheat when supplied by the 24 V battery system. To solve the problem, these devices, which were fortunately located next to the DC/DC converter, were connected to the extra 12 V output.

No arrangements were needed considering switch-off because there are no sensitive devices in the control system. However, if the operating system of the embedded computer is changed, the need has to be reassessed. The same applies if applications that write data on the system drive are run.

Table 3. Maximum continuous electrical power consumption when machine is idle.

Device	Maximum continuous power [W]
Engine electronics	140
Parking brake control valve	30
Motor displacement reduction valve	30
Hydrostatic drive pump	25
Steering valve	25
Embedded computer	20
Cabin display	12
Working hydraulics controller	12
Digital hydraulic valve drivers	10
Main relays	10
IEEE 802.11 wireless module	8
Main PLC (without external load)	7
Emergency stop relay module (with modem)	6
Wheel encoders	6
DGPS receiver	5
Ntrip module	4
Embedded odometry module	4
Remote control module (with modem)	3
AFS resolver	2
Joystick	1
Total	360

6.12 Discussion

Since the machine was built in 2009, it has been utilized in several research projects and technology demonstrations. Ahopelto et al. have used the machine in power management research, experimenting with operation at minimal rotation speed of the engine [7]. Huova et al.

have developed energy efficient multi-actuator control with digital working hydraulic circuit [52]. Tikkanen has experimented with the energy efficiency of displacement controlled working hydraulics [108]. In addition, automated path following, short-range remote control and digital working hydraulics have been demonstrated with the wheel loader at several industrial and academic events. Since the first demonstrations, several hardware changes have been made to the original control system as required by various research projects. It is therefore possible to assess the actual flexibility of the control system.

6.12.1 Control system modifications

To measure the volume flow of the working hydraulic circuit for closed loop displacement control, a volume counter was installed [108]. The sensor outputs incremental signals that enable detecting of the direction of the volume flow. The controller development was done utilizing the MicroAutoBox. Therefore, the sensor was connected to spare inputs on the MicroAutoBox. The pressure controller of the variable-displacement pump of the working hydraulic circuit was also replaced to achieve straightforward displacement control. A fast proportional directional control valve was installed, instead, to control the displacement of the pump. The valve was connected to a current-controlled PWM output at the main PLC.

Eventually, the performance of the Pentium M–based LittleBoard 800 computer was considered to prevent testing of the most advanced controllers. Moreover, multicore support of the xPC Target real-time kernel had been improved. Therefore, the LittleBoard 800 was replaced with a Core i7–based dual-core Hurricane-QM57 with a core clock frequency of 2.53 GHz. The computer complies with EPIC Express specification [34], having smaller dimensions than the EBX-compliant [29] LittleBoard 800. However, the Hurricane-QM57 requires an ATX-style power supply with multiple regulated voltages, and has horizontal 8P8C connectors for Ethernet. Therefore, a slightly larger enclosure had to be selected. The conduction cooled EPIC Express board is equipped with a board-sized heat spreader which was used for mounting the board. Both computers can be expanded with PCI-104 boards, but PC/104 support is not included in EPIC Express [34]. Therefore, a quad-channel PCI-104 version of the CAN expansion board was installed. Fortunately, it was straightforward to also modify the previously developed xPC Target driver to support this version. Serial port was left out because it had been minimally utilized and would have required an expansion board or a USB adapter.

Since the dSPACE MicroAutoBox is relatively expensive, it was removed from the machine to be applied to another research platform after the most intense development of the digital hydraulic controller was completed. Because of the upgraded performance of the embedded computer, the digital hydraulic controller was implemented utilizing it. The angular potentiometers were connected to spare I/O of the main PLC. CAN 4 was connected to the embedded computer for communicating with the valve drivers. CAN 3 was connected to the spare CAN of the embedded computer, improving data logging capability. Moreover, having all the CANs available enables computation to be more flexibly divided between the main PLC and the embedded computer if required in future. It is, for example, possible to use the main PLC only as I/O extension to the embedded computer.

However, having the digital hydraulic controller implemented on the embedded computer has its drawbacks: other software development utilizing the embedded computer may prevent the working hydraulics from being operated. Removing the embedded computer for maintenance naturally disables the working hydraulics, as well. It has been planned, therefore, that a simplified controller would be implemented on the main PLC to be used as a backup. This would, however, require CAN 4 to be also connected to the main PLC. Simple proportional controllers could be implemented with the generic embedded module also inside the valve drivers. In that case, the access to CAN 4 would be required for transmitting target velocities or flow values from the main PLC to the valve drivers.

Running the digital hydraulic controller on the embedded computer has endorsed safer methods for developing the xPC Target models: the default standalone model on the system drive of the embedded computer has to be reliable and stable, especially concerning the controller for the working hydraulics. Testing new controllers has to be done with a host laptop by running the loader model on the embedded computer from a USB drive. Furthermore, the new standalone models have to be tested thoroughly from a USB drive before changing the default standalone model on the system drive.

It was not possible to connect the volume counter sensor to the main PLC because there are no compatible inputs for incremental signals. Therefore, a module very similar to the one utilized in wheel odometry was developed utilizing the generic embedded module. The signals were connected to the quadrature decoder inputs of the microcontroller board. The microcontroller was programmed to read the difference register of the quadrature counter every 5 ms and transmit both the raw value and a low-pass filtered value over CAN. The volume counter module was connected to CAN 4 for communication with the embedded computer. This was convenient as the valve drivers of the working hydraulics communicate over the same CAN.

The layout of the control system after the described modifications is presented in Figure 27. Comparing to Figure 26, it can be seen that the original arrangement of one Ethernet and four CANs has been maintained.

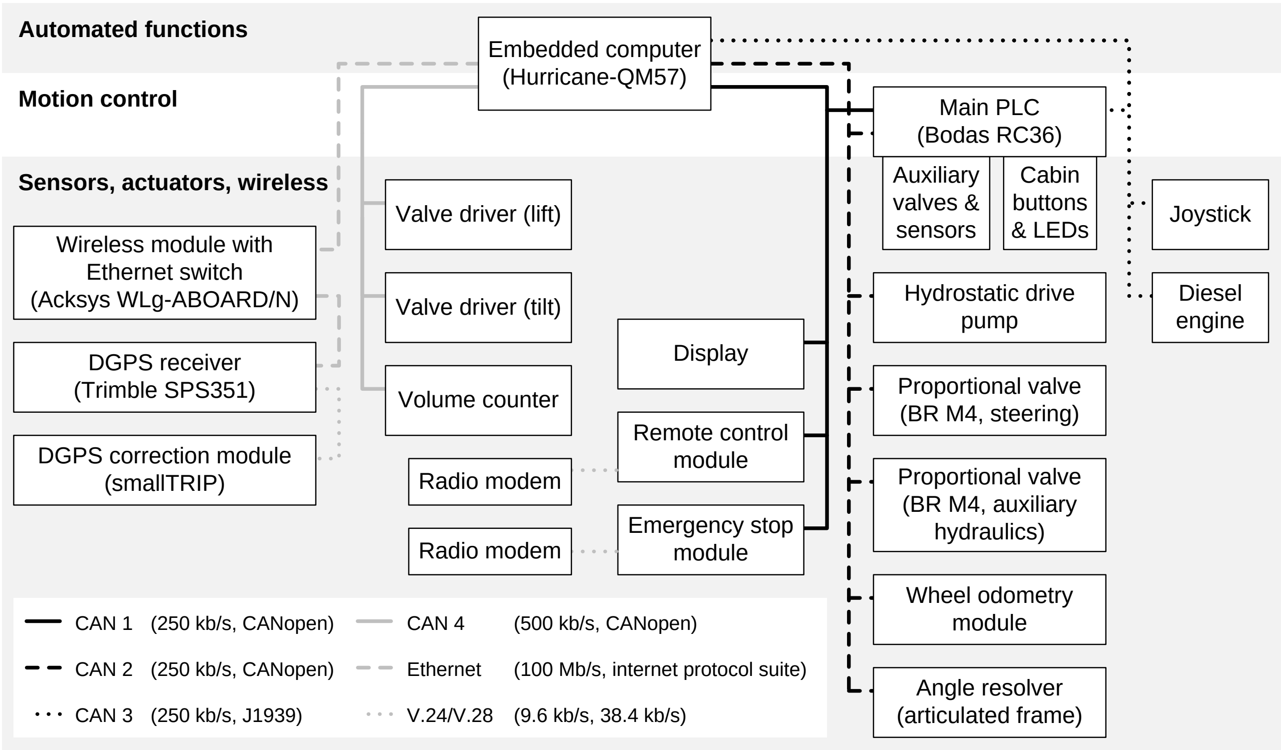

Figure 27. Control system layout after modifications.

6.12.2 Meeting requirements

The hardware architecture of the control system has proven flexible, robust and research-friendly. Since most of the utilized devices are targeted at demanding operating conditions, they have caused very few reliability problems. All the devices cover the minimum operating temperature range specified in Chapter 2. The specified minimum degree of protection, IP55, however, is not met by the Ntrip module. It was installed inside the cabin because it had not been tested according to IEC 60529 [23] and the degree of protection was estimated to be no more than IP34. The original enclosure could also have been changed. The embedded computers and devices based on the generic embedded module were installed in protective enclosures with panel connectors. The enclosures and connectors were chosen to meet IP65, at minimum. Although the assembled enclosures were not tested according to IEC 60529, the installation guidelines of connector and enclosure manufacturers were followed to maintain the degree of protection. Some reliability problems were experienced related to heat management of the linear voltage regulators, as mentioned above. In addition, a sensor fault in wheel odometry caused an excessive sensor supply current to flow through the application-specific board of the wheel odometry module. Unfortunately, the fuse protection of the module had not been rated properly, and the excessive current damaged the board.

In general, the arrangement of the control system follows the reference hardware architecture presented in Figure 20. The low-level control system, however, is distributed over three CANopen networks instead of one, and the data rates are lower than the proposed 1 Mb/s. This solution increases flexibility and improves compatibility with the CANopen slave devices that have limited message or data rates. The joystick was ordered with a J1939 interface instead of CANopen due to a shorter delivery time. Analogue temperature, pressure and position sensors, auxiliary on-off valves and cabin buttons are connected to the I/O of the main PLC instead of separate CANopen I/O modules. This is not optimal considering life-cycle manageability since a replacement PLC needs to have similar I/O to minimize software modifications. Utilizing the three CAN interfaces of the PLC also has a negative effect as the higher number of used CAN interfaces decreases the number of potential replacement PLCs. A separate CAN switch would improve the situation.

The high-level control system is distributed over Ethernet at 100 Mb/s instead of the proposed 1 Gb/s. Therefore, adding machine vision, as estimated in Table 1, requires an upgrade to 1000BASE-T. However, no devices need to be replaced: The embedded computer supports 1000BASE-T, and the rest of the current 100BASE-TX network can be connected to one of the ports of a 1000BASE-T switch. The CAN-Ethernet bridge proposed in Figure 20 is replaced by the quad-channel CAN expansion board of the embedded computer in Figure 27. This solution is smaller, has a lower hardware cost and minimal communication delays. However, replacing the embedded computer, its operating system or the expansion board are challenges considering life-cycle manageability due to driver support and expansion board availability.

The modifications that have been carried out (Figure 26 and Figure 27) have not required any heavy redesign. Having several CANopen-compliant busses enables flexible I/O, sensor and actuator extensions utilizing vendor-independent devices with uniform methods for configuration management. Furthermore, it is possible to add multiple mobile PLCs to distribute computation over CANopen. Where the size, real-time performance or I/O interfaces of commercial CANopen devices are not sufficient, utilizing the generic embedded module presented in Chapter 5 is an efficient method. New embedded computers and advanced sensor and actuator systems can be connected to the on-board Ethernet. An external switch, however, is required since there are no spare Ethernet ports.

There are commercially available replacements for most of the devices utilizing the generic embedded module. Some devices, however, need more than one commercial device for replacement. For example, the valve drivers of digital hydraulics could be replaced with CANopen I/O modules or mobile PLCs with 20 on-off outputs. An external output stage would be required, however, to implement fast current switching. Another option is to utilize devices that have both high side and low side driving outputs. In this case, several I/O modules would be applied to replace each 20-channel valve driver. Careful scheduling analysis would be needed to ensure a deterministic communication delay to these I/O modules. The emergency stop system could be replaced with a commercial one, but the CANopen interface would have to be implemented with a mobile PLC, for example.

The flexibility of the hardware architecture has been further indicated in the development of similar systems on other wheel loaders: A smaller AFS machine with distributed low level computation [6] has been equipped with embedded computers, a GNSS receiver, wheel odometry and emergency stop modules. In addition, advanced sensors like lidars and machine vision cameras are connected via Ethernet. The flexibility of the architecture also enabled rapid development of automated path-following and digital working hydraulics on another wheel loader for industrial demonstration. The frame of the wheel loader is similar to the one presented in this chapter, but in this case the original mechanical parts of drive train and steering were preserved. The machine was ready for demonstration six months after the functional requirements were specified.

The control systems presented in Chapter 1 have computers, sensors and communication similar to the control system presented above. The hardware architectures, however, are different, and do not meet the requirements presented in Chapter 2. The systems that do meet the data rates listed in Table 1 do not tolerate the specified operating conditions or have poor life-cycle manageability. This is due to proprietary communication over internet protocol suite even in the low-level control system and utilization of various expansion boards in embedded computers.

7 Case 2: Automated excavation

A small commercial skid-steered wheel loader was modified for short-range remote control in previous research [123]. Three similar machines were built for various research projects and technology demonstrations. The electronic control system was implemented with a robust commercial embedded computer with display and distributed I/O modules. The control system of two of the machines was then extended to support multi-machine operation, lidar-based path following and stereoscopic real-time video for remote operation. Moreover, a commercial backhoe excavator attachment was modified and interfaced with the control system.

In this chapter, the functional requirements for the control system are listed and the implemented control system of the wheel loader and the excavator attachment is described. The research applications of the machines are discussed and automated emptying of the excavator bucket presented in detail. Meeting the functional requirements as well as the general requirements of modularity, flexibility and robustness are discussed.

7.1 Functional objectives

The control system has to support operation in a fleet of several machines. The machine may be controlled manually either on-board or remotely. The remote operator may stand next to the machine or be located in another city. In addition to real-time video, load information has to be available for the remote operator.

To enable automated excavation, the excavator attachment has to perform closed loop control of the joint angles. Moreover, to maintain the flexibility of the original machine, the modifications must not make installing and removing the excavator more difficult.

7.2 Construction of wheel loader

The wheel loader and the excavator attachment suit research use well: although the machine is compact, the mechanical and hydraulic structures have similarities to larger machines (Figure 28). The wheel loader is modified from a commercial machine of the Avant Tecno 300 series. The machine is skid steered and has a throttle controlled hydrostatic power transmission with four hub motors. The maximum output power of the diesel engine is 15 kW. There is a variety of attachments available for the machine.

Figure 28. Modified wheel loader with excavator attachment.

The original machine has mechanically operated valves which have been replaced by an electronically controlled stackable mobile proportional valve. The valve has six spools: two for travel and one each for boom, bucket, telescope and auxiliary hydraulics outlet. The valve has a load sensing port for measuring the maximum load pressure of the actuator ports. A pressure transducer with current output was installed in this port. In addition, there are on-off valves for toggling between one and two pumps as well as locking the boom and bucket. An electrically actuated pressure relief valve is used to control the supply pressure according to load sensing. The rotation speed of the engine is controlled by an electrical actuator instead of the original mechanical accelerator cable. There are quick couplings for the auxiliary hydraulics. A multipole connector for electric supply and CAN has been added. Therefore, it is possible to extend the CANopen-based control system to attachments.

7.3 Construction of excavator

The excavator attachment, shown in Figure 28, is modified from Avant Backhoe 205. It has four hydraulic cylinders for slew, boom, stick, and bucket movements. The original mechanically operated valves have been replaced like the ones of the wheel loader. An excavator control module has been designed utilizing the generic embedded module. The control module can be configured to compensate the typical nonlinear characteristics of proportional valves, for example. [63]

The proportional valve has integrated current amplifiers. The amplifiers are controlled with a voltage signal. The range of the signal is proportional to the battery voltage. The amplifiers have low-pass filters at control signal inputs, enabling PWM signals to be used. The valve also has a measurement port for maximum load pressure. Similar to the valve on the wheel loader, a pressure transmitter with current output was installed in this load sensing port.

7.4 Control system of wheel loader

The layout of the control system of the small wheel loader utilized with the excavator attachment is presented in Figure 29. To meet the requirements of Chapter 2, the control system is distributed over CAN and Ethernet, utilizing CANopen and internet protocol suite, as proposed in the reference hardware architecture in Figure 20. For reasons of size, cost and device availability at the time of building the machine, sensors and actuators with analogue interfaces were applied instead of CANopen versions. The data signalling rate of CAN is 250 kb/s instead of the proposed 1 Mb/s. The initial tests revealed that the utilized CANopen I/O modules were not able to process bursts of several messages at data rates of 500 kb/s and above. On the other hand, the utilization of I/O modules instead of separate CANopen sensors and actuators results in less protocol overhead and, therefore, a lower network load. The Ethernet also has a data rate lower than proposed by the reference hardware architecture. 100 Mb/s was considered sufficient since the machine vision cameras are connected to a dedicated image processing computer via IEEE 1394.

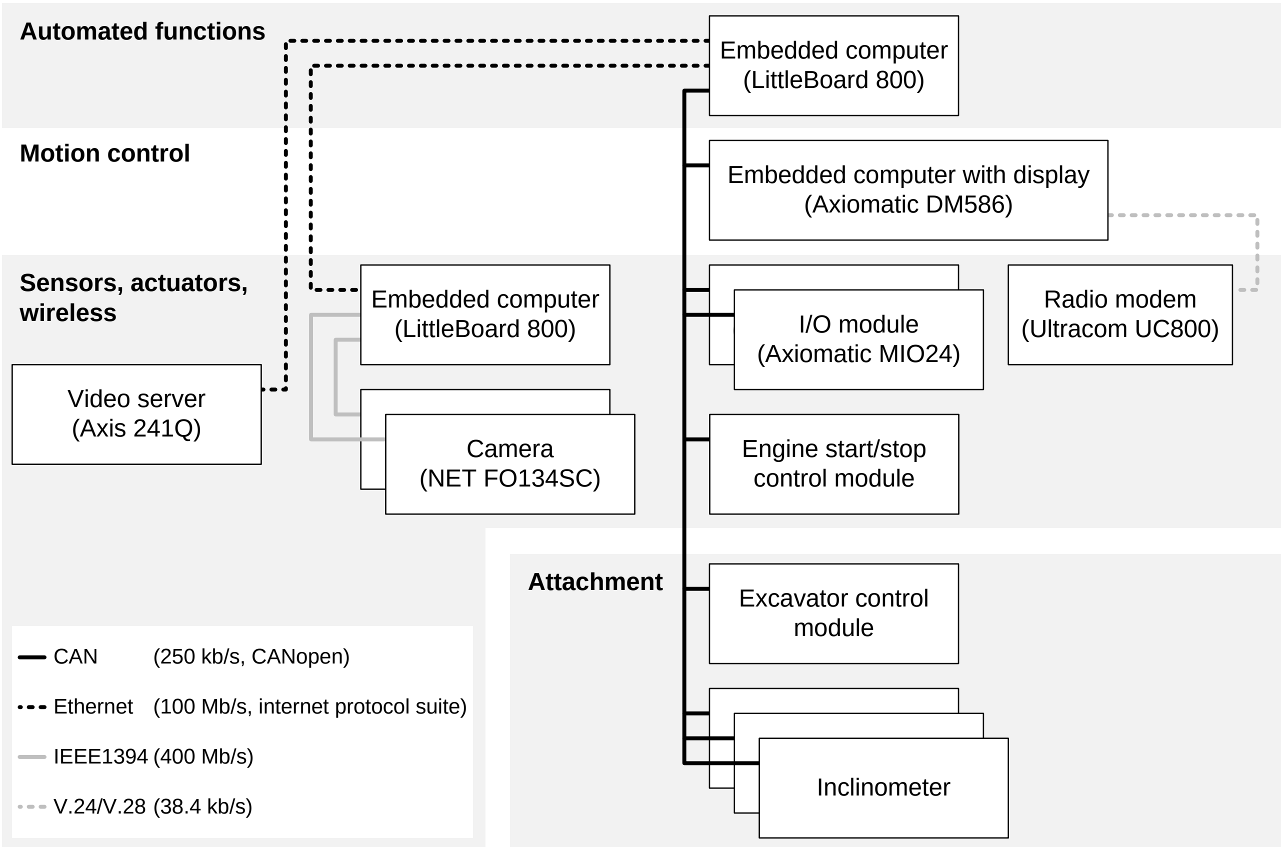

Figure 29. Control system layout.

For manual operation on board, the machine has a steering wheel, a joystick and a gas pedal, all outputting a voltage signal. The signals are measured by two generic CANopen slave I/O modules. In addition, the outputs of the hydraulic pressure transmitters, wheel odometry sensors and the position sensor of the engine actuator are connected to the I/O modules. The modules control the hydraulic valves directly and the engine actuator through a separate H-bridge board. Because the control system of the machine was originally designed for direct teleoperation, the odometry sensors were not intended for closed-loop velocity control. Therefore, the odometry sensors do not indicate the direction of travel, and the conventional pulse counter inputs of the CANopen I/O modules were considered sufficient.

For flexibility and small size, a separate CANopen compatible module was designed and built for controlling the starter, the glow plugs and the stop solenoid. Since the design of the generic embedded module was not finished at the time, another prototyping microcontroller board with some similar features was used. The same software development tools and programming hardware were utilized. However, the applied microcontroller board has a larger size, inconsistent board-to-board connector arrangement, lower performance and no option to install a V.24/V.28 transceiver or bypass the CAN transceiver. Since the applied board was not designed for long-term utilization, there are no more compatible spare boards available. However, the generic embedded module has the I/O and performance to replace the utilized microcontroller board. The application-specific board, however, would need to be redesigned to match the board-to-board connectors of the generic embedded module.

The low-level motion controllers and CANopen master functionality were implemented on an embedded computer running simple embedded GNU/Linux. The DM586 computer also has a bright monochrome display for presenting sensor signals and adjusting control parameters. The motherboard has interfaces for CAN, V.24/V.28 serial and Ethernet. There is soldered flash that can be used as a system drive. The software was developed and compiled on a laptop running a binary-compatible distribution of GNU/Linux.

A radio modem for short-range remote control was connected to the serial port of the DM586. The DM586 was programmed to choose the target values for velocity, steering and working hydraulics between three possible sources: the on-board operator, the short-range remote operator or via CANopen from another embedded computer. In addition, the DM586 can route target values to the excavator control module.

A Pentium M–based LittleBoard 800 embedded computer was included for implementing automated functionality and routing data for multi-machine operation and direct long-range teleoperation. The computer was equipped with two expansion boards on the PC/104-Plus bus: one for CAN, the other for IEEE 802.11 wireless networking. The computer was configured to run GNU/Linux from a CompactFlash memory card.

Another LittleBoard 800 with GNU/Linux was utilized for processing stereoscopic images. A PCI-104 expansion board for IEEE 1394 was installed for communication with the two machine vision cameras. In addition, robust video cameras with analogue output were utilized for remote monitoring. A video server was included for transmitting the analogue video content over the IEEE 802.11 wireless connection. No separate Ethernet switch was required for connecting the video equipment since the LittleBoard 800 has two integrated Ethernet adapters.

The bottom right corner of Figure 29 shows also the CAN devices installed on the excavator attachment. If the excavator is removed from the wheel loader, a bus terminating cap has to be mated with the CAN connector to maintain proper termination.

7.5 Excavator control module

An excavator control module was designed and built utilizing the generic embedded module. The application-specific board was designed to have input circuitry for the load sensing pressure transmitter and a linear potentiometer for slew cylinder measurement. Transistors were included for shifting the voltage level of PWM outputs for valve control.

A linear voltage regulator was considered sufficient since the wheel loader has a 12 V battery system and the current consumption of the excavator control module is less than 100 mA. Wire terminals were included for all the sensors, valves, power supply and CAN. The excavator control module was mounted on top of the proportional valve, minimizing the length of valve control cables.

7.6 Joint angle measurement

The excavator control module was first programmed to perform simple closed loop control of the slew cylinder. For this, a sealed long-life linear potentiometer was mounted parallel to the slew cylinder. [64] Because the results were encouraging, more sensors were added [65]. In addition to the slew cylinder sensor, there are three inclinometers measuring the absolute positions of the main boom, stick boom, and bucket. The arrangement is shown in Figure 30 where the boom, stick, and bucket inclinometers are marked with numbers 1, 2, and 3, respectively. The inclinometer module has been developed at the Department of Intelligent Hydraulics and Automation utilizing the same microcontroller and software development tools as with the generic embedded module [50].

The inclinometers have MEMS accelerometers which have a limited bandwidth. This is not, however, considered a problem in this application. The inclinometers also have MEMS gyroscopes that can be enabled in case the bandwidth has to be extended. The inclinometers have a CANopen compatible interface so they are simply connected using 4-pole cables that supply power and communications.

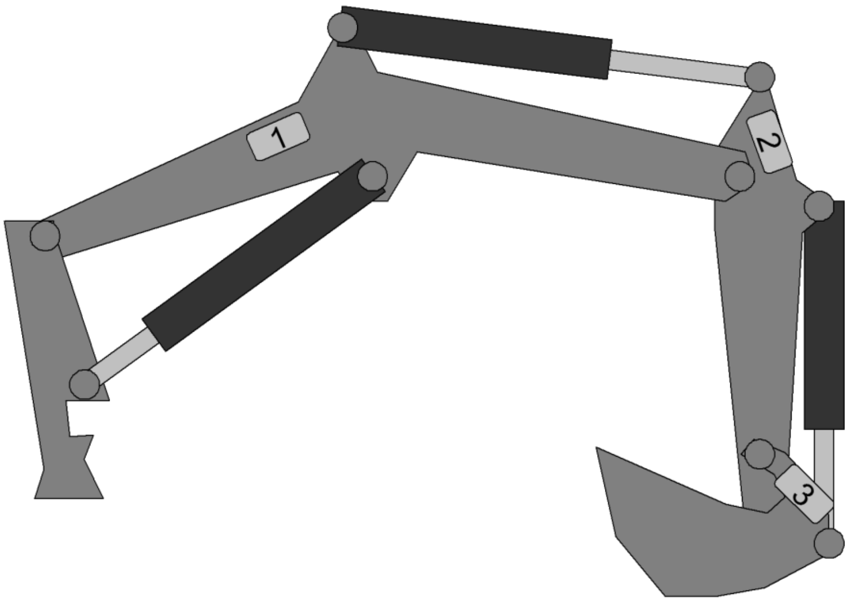

Figure 30. Inclinometer installations on excavator.

Because there is no inclinometer installed on either the wheel loader or the excavator frame, the actual joint angle of the base boom cannot be calculated as the difference between two sensor signals. It is, however, possible to use inclinometer 1 alone for relative measurement of the base boom angle, assuming the wheel loader stays at rest. Moreover, it is possible to cancel the offset every time the wheel loader has been moved by lifting the base boom into a known angle. Nevertheless, lifting the entire machine during operation, for example by pushing the excavator bucket against the ground, generates an error that is not straightforward to detect.

7.7 Video

Video cameras were installed for demonstrating direct teleoperation of the excavator without line of sight to the machine. Taking into account the operating conditions of a wheel loader, two robust cameras targeted at machinery applications were selected. One of the cameras was mounted high on the wheel loader to view the working area of the excavator. The other was mounted on the stick boom of the excavator, showing the bucket. The installed cameras are shown in Figure 31: the one viewing the working area is on the left under the large plastic enclosure, the one on the stick boom on the right. The bucket camera was installed to give a detailed view for the remote operator, but also to test the functionality and durability of the camera at an extremely demanding mounting location. Both cameras are supplied directly from the battery system. Because one of the cameras was mounted on the excavator, an extra connector was added in the camera cable to be disconnected when removing the excavator.

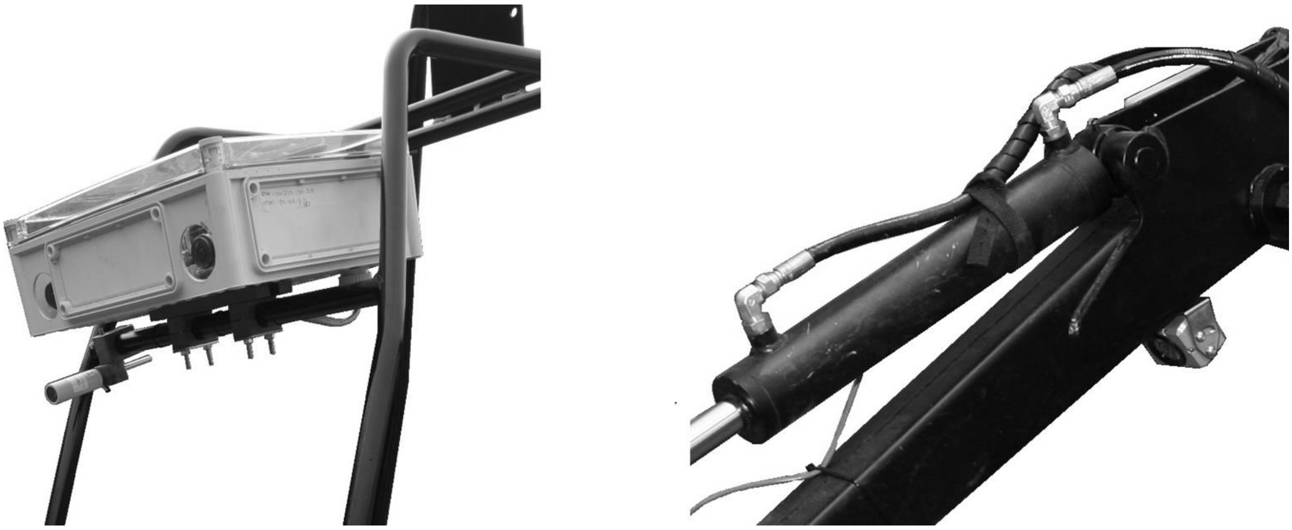

Figure 31. Cameras on wheel loader and excavator stick boom.

Since the cameras output an analogue video signal and IEEE 802.11 wireless networking was considered most feasible for video transfer, a 4-channel Ethernet video server with internet protocol suite was installed on the wheel loader. The server was located inside a compartment for protection against dust and rain. The video server was configured to use Motion JPEG compression for minimal processing delay. The first tests and demonstrations were carried out when the embedded computers shown in Figure 29 had not yet been installed. Therefore, an outdoor IEEE 802.11 wireless AP was mounted on the wheel loader.

In further research conducted by the Department of Automation and Systems Technology at Aalto University, stereo vision was applied. [106] Two machine vision cameras and lenses were installed inside a protective enclosure shown in Figure 31 on the left. The lenses have set screws to lock the adjustable zoom and focus. Since both cameras are fixed into one enclosure, it is possible to move the entire stereoscopic system between research platforms without repeating stereo calibration. Due to previously developed software and experience, cameras with IEEE 1394 interface were selected instead of 1000BASE-T Ethernet. Since real-time image processing is computationally demanding, a dedicated LittleBoard 800 computer with a 3-channel IEEE 1394 adapter was installed inside the same enclosure. In this way it was also possible to avoid problems related to maximum length of IEEE 1394 cables and utilize commercial Beta connectors. Moreover, it is straightforward to install hardware synchronization circuitry between the cameras if needed.

7.8 Electrical power supply

To be able to utilize the original starter and engine controls, the 12 V electrical system of the commercial machine was preserved. Most of the devices of the control system can be supplied directly from the battery system. However, it was noticed in initial tests that the battery has to be almost fully charged when starting the engine to prevent the computers and I/O modules from resetting. In addition to occasional file system errors, the rebooting caused another problem: since the rotation speed of the diesel engine is controlled by one of the computers, a reboot during engine start often resulted in the engine not starting at all. Therefore, a small auxiliary battery was connected through a Schottky diode as presented in Figure 32.

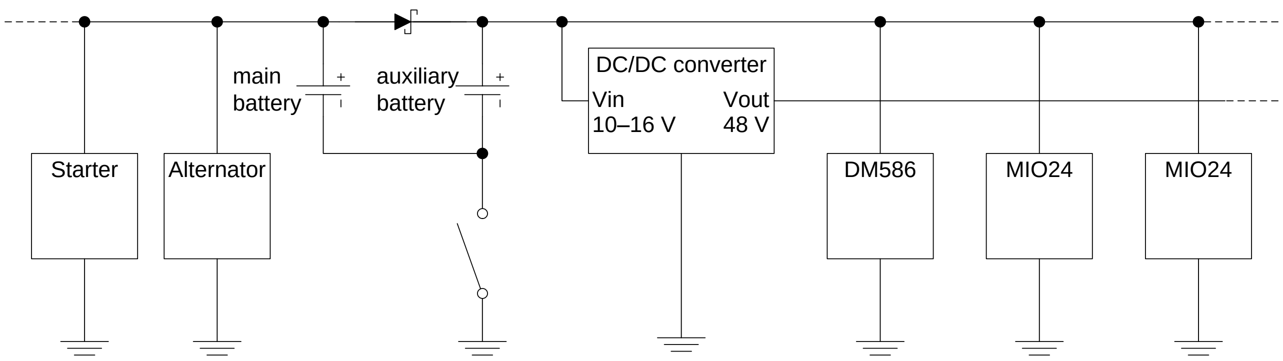

Figure 32. Electrical system with auxiliary battery.

The IEEE 802.11 AP utilized initially for video transfer is a Power over Ethernet (PoE) device. Because a suitable PoE power injector for vehicle use was not available, an automotive DC/DC converter with a 48 V output was utilized. The converter was installed inside the side compartment due to insufficient degree of protection. The entire control system was planned to be operated for testing, development or calibration without the engine running. Because fitting a large battery in the small wheel loader was not feasible, a connector was installed for external power supply.

7.9 Automated excavation functions

As the first step in developing automated excavator control, a simple closed loop controller for slew movement was used. The operator was able to store the desired trajectory points and command the slew cylinder to follow them. [64] The concept was then extended to all four cylinders, which enables automatic emptying and return of the bucket, for example [65].

A block diagram of the excavator controller is shown in Figure 33. The presented controller software is run by the excavator control module of Figure 29. The joystick positions and commands for closed-loop control are received from the DM586 embedded computer of the wheel loader in CANopen Process Data Objects (PDO). In addition, the angular position PDOs transmitted by the inclinometers are received. The valve control signals are produced with PWM outputs of the excavator control module. In addition to closed-loop control, the valves can be open-loop controlled according to the joystick positions. The signals are processed according to parameters that can be set using the CANopen interface. The excavator control module was programmed to estimate the required volume flow and request it from the DM586 embedded computer of the wheel loader in a PDO. Furthermore, the load sensing pressure of the proportional valve is transmitted to the DM586 embedded computer in another PDO. To make the slew cylinder position available to the entire control system, the excavator control module may also transmit the cylinder position in a PDO.

Because the inclinometers measure the angle relative to gravity vector, the controller calculates the difference between two inclinometers over a joint to obtain the joint angle according to (3) and (4).

$$\theta_{bucket} = \theta_3 - \theta_2 \tag{3}$$

$$\theta_{stick} = \theta_2 - \theta_1 \tag{4}$$

Since there are only three inclinometers, the angle of the base boom is obtained directly from the signal of the inclinometer 1. As stated above, this may cause an offset. However, if the wheel loader keeps steady, the offset is not a problem considering this controller because the trajectory points have the same offset when they are stored.

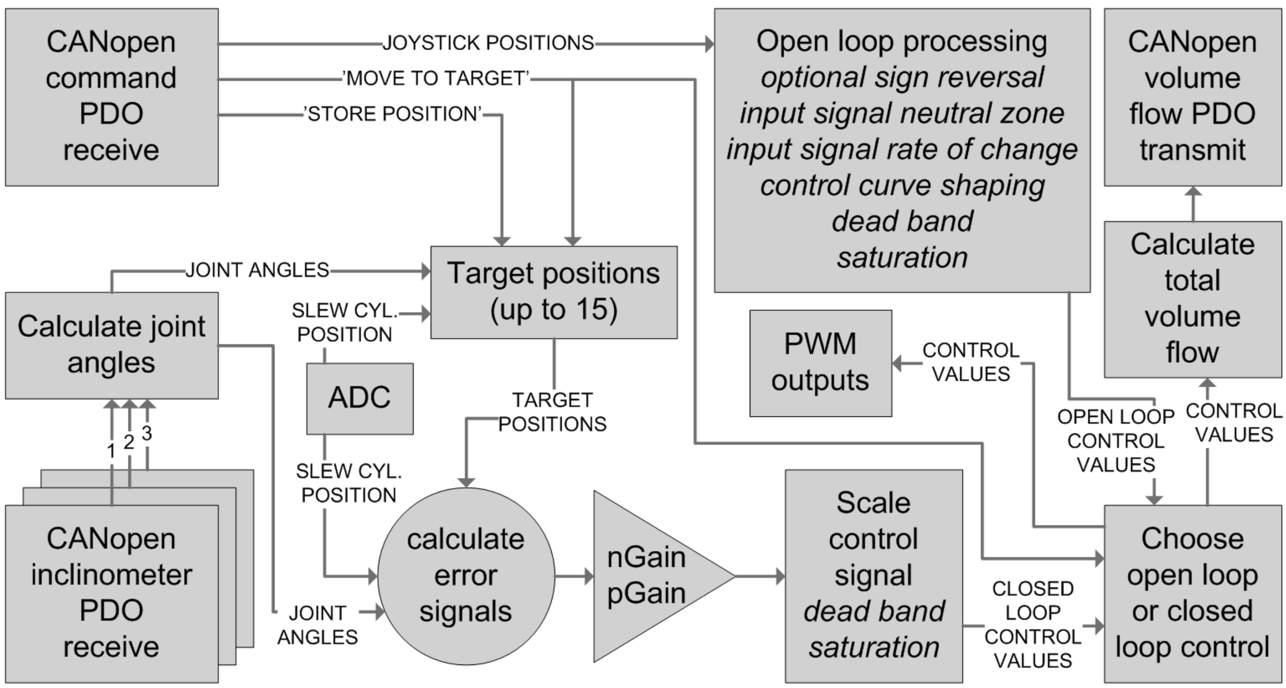

Figure 33. Excavator controller block diagram.

Because the inclinometers are based on accelerometers, there is some disturbance in the angle signals as the machine vibrates or the bucket is hit against the ground. Therefore, the maximum angular velocity of the signals is limited to 200 °/s. The effect of the rate limiter on the bucket angle is shown in Figure 34.

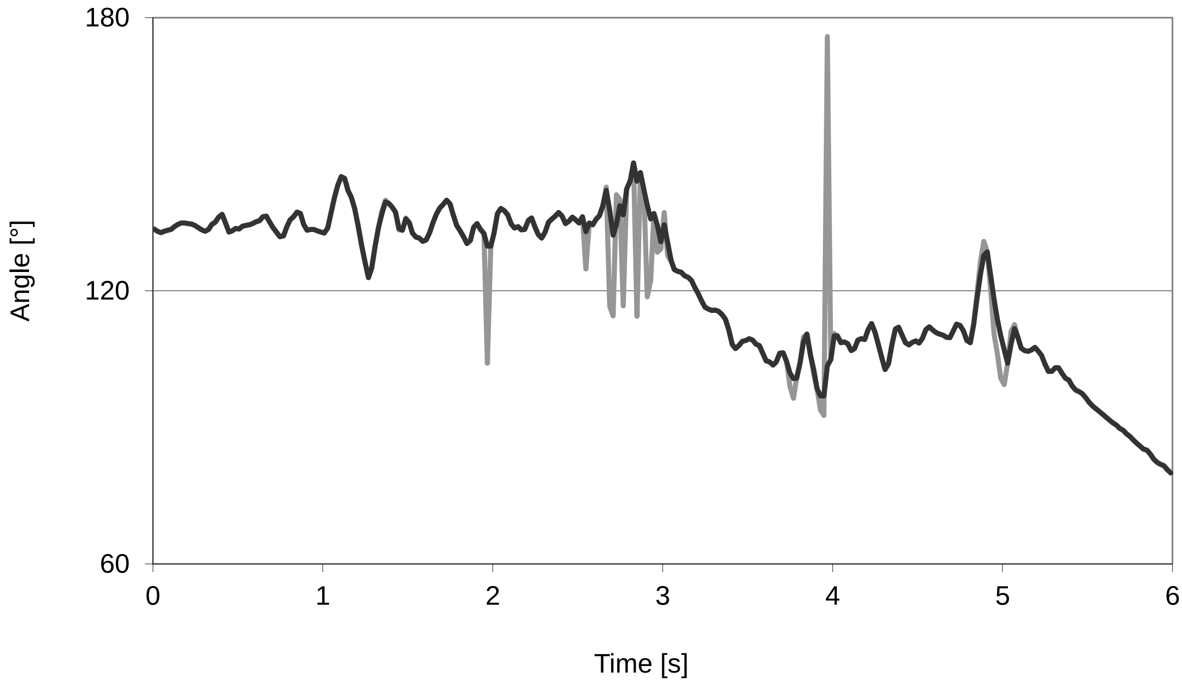

Figure 34. Effect of rate limiter on bucket angle signal.

Up to 15 trajectory points can be stored during open loop control. When commanded, the controller will move the excavator into one of the trajectory points. The position controller has an individual proportional controller for each cylinder. This typically results in a slightly curved bucket trajectory. There is, thus, no path-following controller. Therefore, the trajectory points have to be selected so that the order of the joint movements is insignificant. Total error is calculated from the relative position errors of cylinders that are assumed uncorrelated, e_{slew}, e_{boom}, e_{stick} and e_{bucket}, according to (5).

$$e_{tot} = \sqrt{e_{slew}{}^2 + e_{boom}{}^2 + e_{stick}{}^2 + e_{bucket}{}^2} \tag{5}$$

If the total error stays below a set limit a set settling time, the controller will switch back to open loop control. The parameters were set to 3 % total relative error and 500 ms settling time. These limits were experimentally found suitable for the excavation application, resulting in steady-state position error of less than 10 cm.

7.10 Tests of automated excavation

The performance of the excavator control module was tested in a ditch-digging scenario where the control system helps the operator empty the soil from the bucket in a pile.

7.10.1 Test setup

The control system of the wheel loader was configured to send a ‘store position’ command when a display button on the DM586 is pressed. A button on the joystick was configured to trigger a ‘move to target’ command to be transmitted. The index of the stored position was set to cycle from 1 to 3 for both commands, which enabled bucket emptying and return functionality:

1. over digging point, ready to fill bucket
2. soil in bucket, boom over emptying position
3. stick boom and bucket extended at emptying position

These stored positions are illustrated in Figure 35.

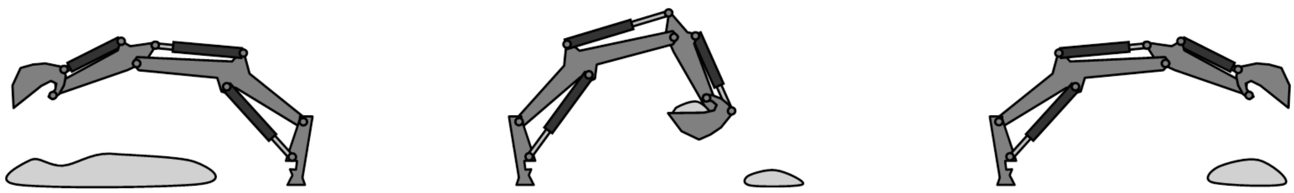

Figure 35. Stored excavator positions for automated bucket emptying and return.

A fourth trajectory point could be introduced if the soil is dug so deep that the base boom has to be lifted before slewing over the emptying position. Nevertheless, the three trajectory points are sufficient to prove that the concept works.

Because the hydraulic system of the wheel loader has a fixed-displacement pump, the control system of the wheel loader was also programmed to control the diesel engine according to the volume flow request from the excavator. The gain parameters of the proportional controllers were tuned experimentally. Because the modified excavator frame is not very steadily supported, the controller gains have to be quite small to prevent the wheel loader from moving on the ground.

7.10.2 Results

The system was tested by first doing an excavation cycle manually and storing the required trajectory points. Figure 36 shows the joint angle signals during the manual excavation cycle. The vertical dash lines show the three trajectory points that were stored.

Between the stored points 1 and 2 the bucket is first filled using the bucket and stick cylinders and then moved over the emptying position using the boom and slew cylinders. Between the stored points 2 and 3 the bucket is emptied using the stick and bucket cylinders.

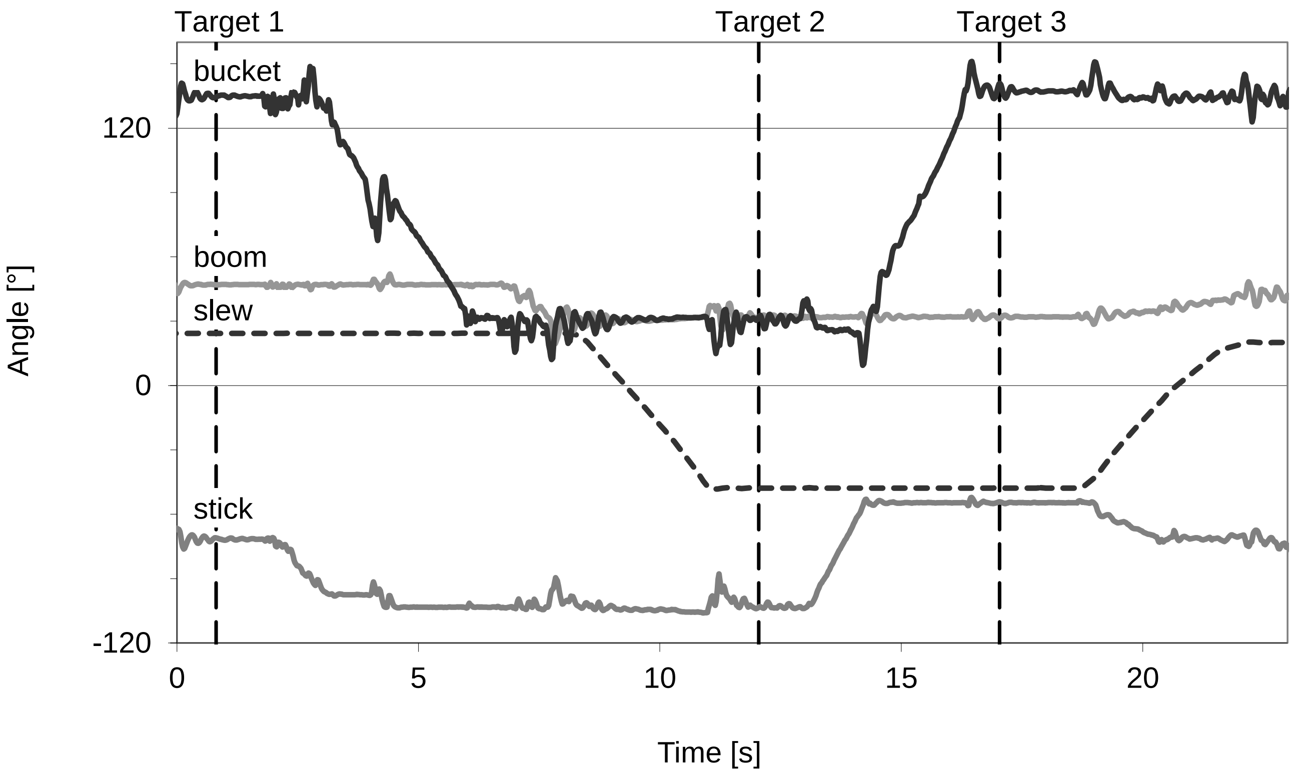

Figure 36. Manual excavation cycle.

Figure 37 shows an excavation cycle that includes the automatic emptying and return of the bucket. The grey background indicates manual control. The vertical dash lines indicate the instant when a 'move to target' command is sent, and the fixed lines indicate when the target is reached. Target number 3 is actually not reached at all because the operator sends the command 'move to target 1' as soon as the bucket has emptied at 19.5 s.

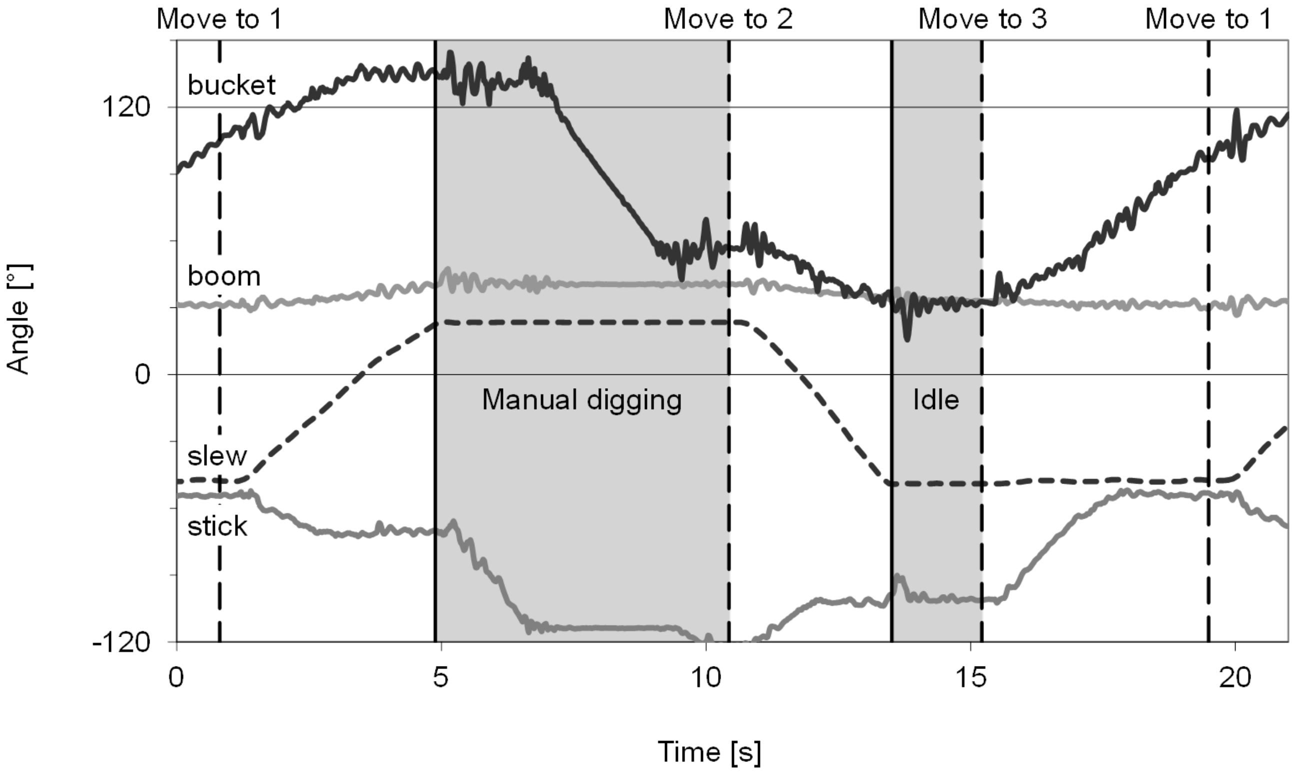

Figure 37. Excavation cycle with automatic emptying.

In this case, the control system is simply cycling the three target positions. Considering bucket emptying in particular, the control system could change to target 3 (bucket emptying) automatically as soon as target 2 (over emptying position) is reached. In Figure 37 the excavator is idle 1.7 s after reaching target 2 because of waiting for input from the operator. Moreover, the control system could simply wait a short time at target 3 to let the soil fall off the bucket and then return to target 1.

Based on the tests, conventional mobile proportional valves and low-cost inclinometers can perform closed-loop position control for operator assistance. The performance and I/O features of the generic embedded module were also sufficient. The control software can be quite simple, but there are several parameters to configure. Although the functionality of the developed system is simple compared to the automated excavation systems presented in Chapter 1, also the required hardware is simple and low-cost. Moreover, the developed controller demonstrates the versatility of the generic embedded module. Based on the results, the position controller can make excavation work easier. The presented system could improve the efficiency of novice operators, in particular.

7.11 Discussion

In addition to automated excavation, several research topics have been covered utilizing the modified small wheel loaders and the excavator attachment. The research has been conducted in co-operation between the Department of Intelligent Hydraulics and Automation at Tampere University of Technology and the Department of Automation and Systems Technology at Aalto University in the Finnish Centre of Excellence in Generic Intelligent Machines Research.

Myrsky describes modular software implementation of automated functionality and communication over the Internet [80]. Hölttä et al. utilize the small wheel loaders in a case study on user interface framework for control of multi-robot systems [53]. Terho has utilized the stereo camera system in stereoscopic teleoperation as well as calculating 3D geometry of the surroundings of the machine [106][107]. Uusisalo has researched the effect of short-range remote control and vibrotactile feedback on performance and user experience with the excavator attachment [121]. Furthermore, the small wheel loaders and the excavator attachment have been used in several technology demonstrations for industrial and academic audiences.

7.11.1 Control system modifications

The flexibility of the control system was tested in practice as the control system was extended and modified for different research topics. As mentioned above, the video streams transmitted by the Axis 241Q video server were initially routed through an IEEE 802.11 wireless AP. As the LittleBoard 800 embedded computer with an IEEE 802.11 expansion board was installed, it was straightforward to connect the Ethernet cable to a spare Ethernet port on the computer instead of the AP. Furthermore, GNU/Linux enables flexible routing and encryption of the data. On the other hand, more system maintenance is required. Therefore, applying an embedded computer running GNU/Linux for wireless networking alone is not feasible.

The stereoscopic system was designed at the Department of Automation and Systems Technology at Aalto University. The system was aimed to be easy to move between different machines and other research installations. Since both cameras and the image processing computer are installed inside the enclosure, all communication with the system is conducted via Ethernet. In addition, power supply from the battery system had to be connected. The stereoscopic system was successfully changed between machines during the research. However, the DC/DC converter that had been originally installed inside the enclosure had to be replaced because it did not have a wide supply voltage range and was compatible only with 24 V battery systems.

7.11.2 Meeting requirements

The CANopen-based system with distributed I/O proved to be a flexible platform for adding automated functionality: the wheel loader and the excavator are fully controllable by the

LittleBoard 800 embedded computer over CAN. In addition to communicating with the DM586, the LittleBoard 800 is also able to read sensor data directly from the messages sent by the I/O modules. Moreover, with the CAN-based system installing the excavator attachment requires connecting only two cables: one for CAN and electrical power, the other for the camera on the stick boom.

The data transfer requirements of Chapter 2 are met. However, the arrangement of the stereoscopic system, as explained above, does not follow the reference hardware architecture proposed in Figure 20. Utilizing Ethernet cameras instead, there would be no need to maintain an embedded computer with a dual IEEE 1394 interface. The presented system with IEEE 1394, however, makes 100BASE-TX Ethernet sufficient for the rest of the high-level control system. Similar improvement in life-cycle manageability would be achieved if the CAN expansion board of the other embedded computer were replaced with a separate CAN-Ethernet bridge and the IEEE 802.11 connectivity were realized with an external module as proposed in Figure 20.

Some devices of the control system do not meet the operating conditions required in Chapter 2: Although the machine vision cameras are installed inside an IP55 enclosure, they do not have a sufficient range of operating temperature. The same applies to the AXIS 241Q video server and the DC/DC converter supplying the IEEE 802.11 AP. Nevertheless, the applied enclosures and mounting locations seem to have protected the equipment during the research applications. For long-term research in demanding conditions, additional sealing, heating and possibly mechanical suspension of some of the enclosures has to be applied. Some reliability problems have been experienced, mainly related to file system errors due to unexpected switch-off of the embedded computers. Therefore, one of the methods presented in subchapter 4.1.4 has to be applied.

Comparing the control system presented above to the systems presented in Chapter 1, the key difference is the utilization of CANopen in the low-level control system. The generic CANopen devices and the well-defined system management process improve life-cycle manageability. The smaller number of expansion boards in the embedded computers also has a positive effect.

8 Conclusions

Considering the first research question, there are several possible solutions for on-board networking of a machine. The applicability of any communication technology, however, has limitations. USB and IEEE 1394 are not widely available in robust sensors, actuators and I/O modules, have short segment length and physical topologies that require switches or hubs. Moreover, developing software for USB or IEEE 1394 devices is not as straightforward as with the other networks and buses discussed. There are no well-established industrial connectors. LIN and V.24/V.28 serial communication have a low network throughput and limited availability of devices.

Although the network throughput of CAN is not sufficient for all advanced sensors, a CAN-based general-purpose protocol is a good choice for most devices of an electronic control system of a mobile machine for cost and availability reasons. Moreover, this enables the control systems of manual and automated machines to be developed and maintained side by side. In addition to CAN, automated functionality usually requires a network with a high data rate, Ethernet being the only practical solution. For configuration and maintenance, an ideal combination of technologies would be CANopen and POWERLINK or DeviceNet and Ethernet/IP.

Since industrial Ethernet protocols are not widely supported by GNSS receivers, laser scanners, machine vision cameras etc., a standard Ethernet with conventional internet protocol suite is almost mandatory. Special attention needs to be paid to scheduling analysis and connector solutions. In addition, specific devices require V.24/V.28 serial ports or an IEEE 1394 interface. However, GNSS receivers, lidars and machine vision cameras, for example, have recently become widely available also with Ethernet interface. Although USB has severe limitations in mobile machinery applications, it is a feasible option for interfacing mass storage, especially removable flash drives.

Addressing to the second research question, the essential device-related design aspects concern the power supply, embedded computing and advanced sensing. The electronic control system for automated operation may increase the loading of the electrical system compared to a manually operated machine. On the other hand, an automated machine may not need as many lights, as much seat heating, etc. It is often possible to utilize similar alternators. With research equipment, in particular, managing the power consumption of the control system when the engine is not running is more critical.

Embedded computers typically require intelligent management of the electrical power supply to prevent file system errors due to unexpected switch-off. With high-performance computers, thermal management is also challenging. Robust expansion boards are relatively expensive. Minimizing the number of different types of bus and network interfaces and utilizing the most common ones improves life-cycle manageability.

Equipment for advanced perception typically requires additional protection: machine vision cameras require protective, temperature controlled enclosures. On the other hand, applying advanced lidar systems to mobile machinery is restricted due to external moving parts.

A small generic microcontroller board may be utilized in intelligent sensor and actuator interfaces, being an answer to the third research question. Several embedded devices for mobile machinery applications were designed utilizing the developed microcontroller board. The approach was found to be flexible and efficient. The same approach could be suitable for commercial prototyping projects and control system development. Using a generic plug-in microcontroller board is a life-cycle-efficient solution because maintenance and software updates can be continued even after the original microcontroller model and software development tools have become obsolete. Although the presented microcontroller board is especially targeted at mobile machinery applications, some of the benefits can also be achieved with commercial microcontroller modules.

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ISBN 978-952-15-3636-6
ISSN 1459-2045