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Performance of smart sensors standards for aerospace applications

***Abstract**. This paper deals with data exchange according to a group of standards IEEE 1451, which runs between a smart sensor module TIM and a supervising system NCAP. The first part of the paper presents the most important idea of IEEE 1451 group of standards: Transducer Electronics Data Sheet, which is a smart sensor description structure in module memory. It also describes the method of exchanging data between the modules and method of storing data in module's memory. Next part describes a multi-platform library, which was created, tested and then described in this paper. The library defines data structures and implements functions for storing data and their exchanging between TIM and NCAP modules. The paper also presents a scenario where all the aircraft systems are equipped with the smart sensor interface in order to simplify maintenance and replace-ability of all units. Finally, all the smart sensor functionality is applied on an aerometric module connected to a PC through CAN bus.*

***Streszczenie.** W artykule przedstawiono zasady wymiany informacji zgodnie ze standardem IEEE 1451 miedzy czujnikiem inteligentnym a układem nadzoru NCAP. Przedstawiono bibliotekę definiująca strukturę danych. Zaprezentowano scenariusz przesyłania informacji między czujnikami inteligentnymi stanowiącymi wyposażenie samolotu oraz przesyłania informacji do PC za pośrednictwem interfejsu CAN. (**Możliwości standardu obsługującego czujniki inteligentne w zastosowaniu do lotnictwa**)*

Keywords: Smart sensor, IEEE 1451, multiplatform library, Air Data Computer, CAN-bus.
Słowa kluczowe: czujniki inteligentne, standard IEEE 1451, CAN.

Introduction

Modern airspace systems are mostly decentralized and can be easily replaced on run and support plug-and-play feature, which is presented in [1]. These systems can be described with group of standards IEEE 1451. They are mostly Line Replaceable Units in aerospace, for example an air data computer with new pressure sensors [2] or flight control systems with intelligent sensors [3]. Group of standards IEEE 1451 is highly universal and can be used in very different areas, e.g. in a smart camera [4] or environmental protection systems [5].

Group of standards IEEE 1451 defines a network composed of smart sensors. This network is created by Transducer Interface Modules (TIM) and one Network Capable Application Processor (NCAP). TIM module can contain one or more sensing elements and one or more actuators. Each embedded sensing element and actuator creates a Transducer Channel. TIM modules are connected to the NCAP module, which connects TIM modules to the superior network and controls them. The TIM module has memory with Transducer Electronic Data Sheet (TEDS), which describes TIM module whose definition is shown in Fig. 1.

Group of standards IEEE 1451 enables to design sensors and actuators network from the beginning of design process. This networked system can be used for simulation, validation and verification [6]. This group of standards defines how sensors can be calibrated and how they support self-validating ability [7]. For error handling and logging data acquisition unit [8] can be included into sensors and actuators network.

System description

TEDS memory contains common description of the TIM module in part named Meta TEDS, detailed description of included Transducer Channels in part named Transducer Channel TEDS, description of physical layer (low rate WPAN, Wi-Fi and Bluetooth are supported, CAN and RFID will be added in future) in Physical Layer TEDS and names of each Transducer Channels in Name TEDS. TEDS can also include memory for user to store his own data (a bytes array, which length depends on manufacturer) in TIM module in End User Application Specific TEDS. Calibration data (linear calibration parameters and general calibration coefficients) for all Transducer Channels in Calibration TEDS, frequency response (table with points, which consists of frequency, amplitude and phase) in Frequency Response TEDS and transfer function (defined by numerator and denominator coefficients or by parameters of zeroes and poles) in Transfer Function TEDS are included as well.

```xml
<? xml version ="1.0" encoding="latin2" ?>
<!-- TIM module description according to standard 1451.0 -->
<TIM>
    <MetaTEDS>
        <TEDSLength> XX </TEDSLength>
        <MetaTEDSDataBlock>
            …
            <TestTime>
                <Type> 12 </Type>
                <Length> 4 </Length>
                <Value> XX </Value>
            </TestTime>
            …
        </MetaTEDSDataBlock>
        <CheckSum> XX </CheckSum>
    </MetaTEDS>
    <userTransducerNameTEDS>
        <!-- User Transducer Name TEDS definition -->
    </userTransducerNameTEDS>
    <phyTEDS> <!-- Physical layer TEDS definition --> </phyTEDS>
    <EndUserApplicationSpecificTEDS>
        <!-- End User Application Specific TEDS definition -->
    </EndUserApplicationSpecificTEDS>
        <!-- list of TransducerChannel TEDS definitions -->
    <TransducerChannelList TransducerChannelNumber="xx">
        <!-- Transducer Channel definition -->
    <TransducerChannel>
        <TransducerChannelTEDS>
            <!-- Transducer Channel TEDS definition -->
        </TransducerChannelTEDS>
        <userTransducerNameTEDS>
            <!-- User Transducer Name TEDS definition -->
        </userTransducerNameTEDS>
        <CalibrationTEDS>
            <!-- Calibration TEDS definition -->
        </CalibrationTEDS>
        <FrequencyResponseTEDS>
            <!-- Frequency Response TEDS definition -->
        </FrequencyResponseTEDS>
        <TransferFunctionTEDS>
            <!-- Transfer Function TEDS definition -->
        </TransferFunctionTEDS>
        <UnitsExtensionTEDS>
            <!-- Units Extension TEDS definition -->
         </UnitsExtensionTEDS>
        <ManufacturersDefinedTEDS>
            <!-- Manufacturer's Defined TEDS -->
        </ManufacturersDefinedTEDS>
    </TransducerChannel>
    ...
    </TransducerChannelList>
</TIM>
```

Fig.1. Description of TEDS in xml file.

TEDS also enables manufacturer of the TIM module to create his own part of TEDS (custom data structure) for each Transducer Channel, named Manufacturer's defined TEDS. For any Transducer Channel, which actuates or measure a physical unit, which can't be described by SI units, TEDS contains Units Extension TEDS with text description. Detailed description of modules TIM and NCAP and TEDS memory are defined in [9].

Each part of the TEDS memory is divided into regions: first region contains length of TEDS memory part, second region contains stored data and last region carries a data checksum. First item in the data region is TEDS header, which numerically identifies region content. TEDS header is followed by Data items. Each Data item has identifier, length of data and data organized in big-endian format. Fig. 2 shows the structure of TEDS memory.

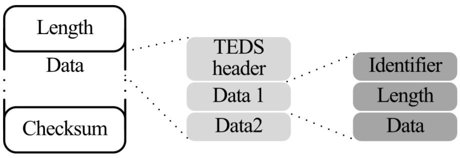


Fig. 2: Structure of TEDS memory.

Transfer protocol between module NCAP and modules TIM is independent on physical layer. Communication process starts within NCAP module by command packet, which is addressed to specific TIM module. This address is dependent on physical layer. When TIM module receives and recognize command, this command is processed and, if is demanded, a response is send. If the response is demanded, NCAP module waits for response from TIM module until time-out occurs. While is NCAP module waiting, communication process is stopped. When module NCAP needs to read TEDS memory, module NCAP periodically sends set of command packets to module TIM and receives response packets. Sensors measurement and actuators can run at communication background. Time diagram with communication between NCAP and TIM modules is in Fig. 3.

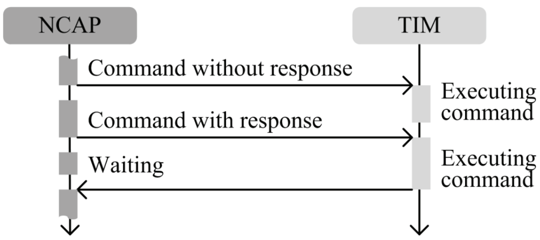


Fig. 3: Time diagram for transfer protocol.

Command packet includes following parts:

- address for specification one Transducer Channel, group of Transducer Channels, all Transducer Channels or module TIM;
- command class specification (command group);
- command (one item from command class), e.g. command for reading TEDS, set actuator value, etc.;
- length of command dependent data; and
- command dependent data.

Response packet has only three parts: flag that represents result of command, length of reply dependent data and data with response.

Results

Multiplatform library was created in order to debug TEDS memory on a PC and on different microcontrollers. The library can load TEDS memory from xml file on PC, which is defined in [10], and can export loaded memory in a header file for microcontroller's program. The library also allows generation of command and response packet and controls communication between TIM and NCAP modules.

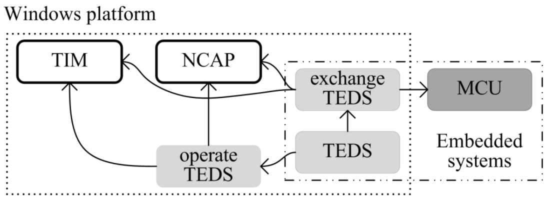


Fig. 4: Structure and dependencies of multiplatform library.

The library is divided into three parts, which are shown in Fig. 4 with their dependencies and using in simulator of communication between TIM and NCAP modules on Windows platform and in embedded systems with Micro Controller Unit (MCU), which runs on Freescale HC12 platform, but can be used in another microcontroller programmable in C. First part, named "TEDS", defines data structures for TEDS memory, transforms data from these XML defined data structures into format described in group of IEEE 1451 standards. This is necessary for data transfer and storage in TEDS memory of the sensor module. Second part of the library, named "exchange TEDS", generates command packets for transferring TEDS memory between TIM and NCAP modules. It recognizes command packets and generates answers to these commands. The both parts are written in C and are multiplatform. Third part of the library, named "operate TEDS" loads TEDS memory from xml file, generates the header file with data structures and generates text description of TEDS memory for its displaying in programme. This part of library was written in C++ programming language and it can be used only as part of MS Windows applications. The first and the second part of the library can be used in TIM and NCAP modules. Some functions in these parts are used only in NCAP module, the rest of functions are used in NCAP and TIM module and in embedded systems with MCU. The third part of the library can be used in an independent program or in simulator of module TIM on PC.

Two applications were created for the library testing: one simulates module TIM and the other application simulates NCAP module. NCAP module simulating application can read TEDS memory and measures values from Transducer Channels sensors of the TIM module. It sets desired values for Transducer Channels actuators of the TIM module. Application simulating module TIM can load TEDS information from xml file and it can generate header file with loaded values for any program with TIM interface. These two simulators can communicate between themselves through serial line, TCP/IP protocol and CAN bus, which is connected to PC with USB to CAN converter. Communication diagram between simulators and Air Data Computer (ADC) with TIM interface is shown in Fig. 5.

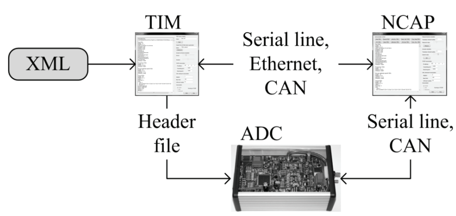


Fig. 5: Communication diagram between simulators and Air Data Computer.

GUI of NCAP module simulator is shown in Fig. 6, of TIM module simulator in Fig. 7.

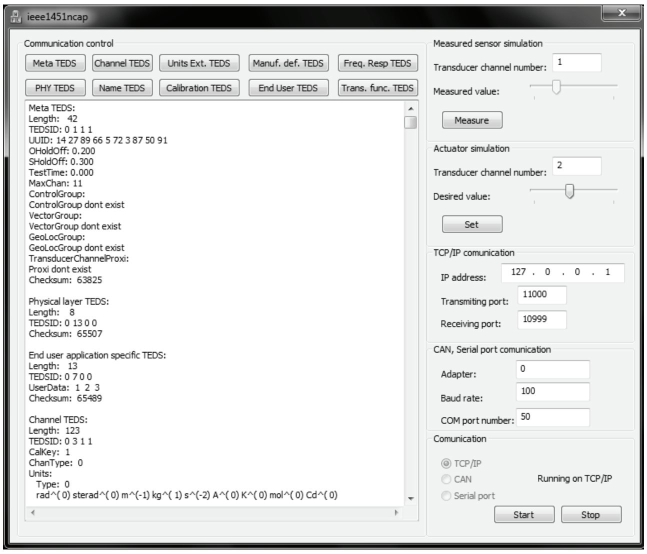


Fig. 6: NCAP module simulator.

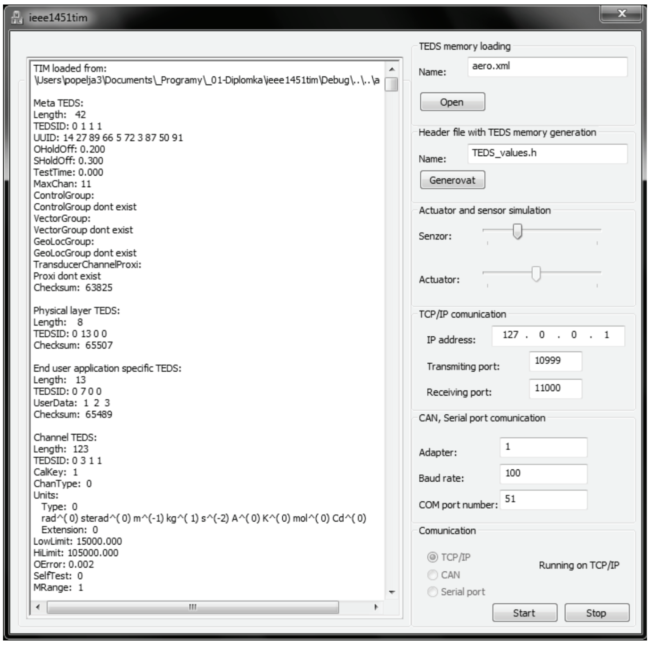


Fig. 7: TIM module simulator.

For existing aerometric system [11] was created a program, which implements earlier described multiplatform library, and description of TEDS memory in xml file. With this programme, the Air Data Computer (ADC) behaves as TIM module and is described by TEDS memory. This ADC contains 11 channels and its structure is on Fig. 8. The ADC has two pressure sensors Memscap SP82, one temperature sensor SMT160-30-92 and other temperature sensor can be connected. Pressure sensors measure static and total air pressure, their inner temperature and have heating resistors. Temperature sensor measures ADC inner temperature. Altitude, true and calibrated air speed and vertical speed are counted from measured values. All referenced values are described in TEDS memory by set of Transducer Channels – sensors, and pressure sensors heating resistors are described as Transducer Channels - actuators.

Content of xml describing Transducer Channel 1 – Static pressure is shown on Fig. 9. Structure of this xml file is reduced from triplet type, length and value. Only content of field value is shown for reducing length of this file. In this Transducer Channel are only mandatory fields of Transducer Channel TEDS present.

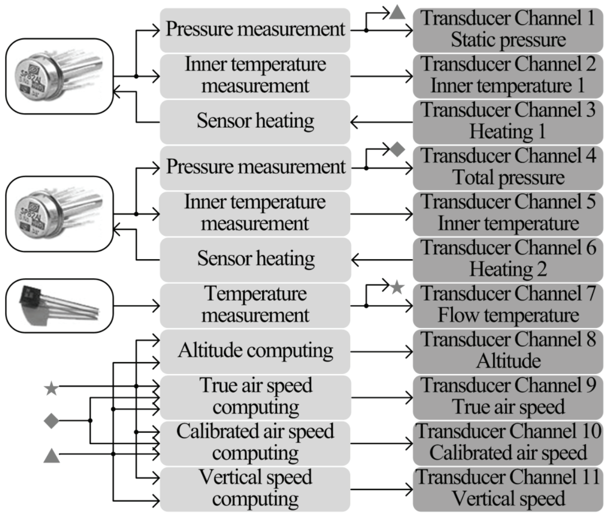


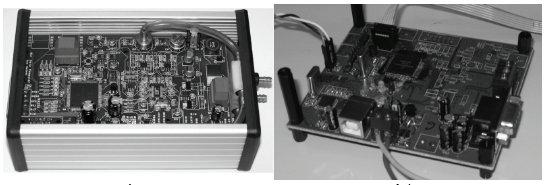
Fig. 8: Description of aerometric system.

```
<TransducerChannelTEDS>
    <TEDSLength> 120 </TEDSLength>
    <TransducerChannelTEDSDataBlock>
        <TEDSID> 0 3 1 1 </TEDSID>
        <CalKey> 1 </CalKey>
        <ChanType> 0 </ChanType>
        <PhyUnits>
            <interpret>0</interpret>
            <radians>0</radians>
            <steradians>0</steradians>
            <meters>2</meters>
            <kilograms>1</kilograms>
            <seconds>-3</seconds>
            <amperes>-1</amperes>
            <kelvins>0</kelvins>
            <moles>0</moles>
            <candelas>0</candelas>
        </PhyUnits>
        <LowLimit> 0 </LowLimit>
        <HiLimit> 100 000 </HiLimit>
        <OError> 0.0002 </OError>
        <SelfTest> 0 </SelfTest>
        <Sample>
            <DatModel> 1 </DatModel>
            <ModLength> 4 </ModLength>
            <SigBits> 24 </SigBits>
        </Sample>
        <UpdateT> 0.001 </UpdateT>
        <RSetupT> 0.011 </RSetupT>
        <SPeriod> 0.001 </SPeriod>
        <WarmUpT> 0.2 </WarmUpT>
        <RDelayT> 0.01 </RDelayT>
        <Sampling>
            <SampMode> 2 </SampMode>
            <SDefault> 2 </SDefault>
        </Sampling>
    </TransducerChannelTEDSDataBlock>
    <CheckSum> 60463 </CheckSum>
</TransducerChannelTEDS>
```

Fig. 9: Content of xml describing Transducer Channel 1.

Program for described ADC includes header file with TEDS memory. Program for described aerometric system was connected to PC with CAN bus and USB to CAN converter and tested for communication with program simulating module NCAP. Program simulating module NCAP read all content of memory TEDS and measured value from one Transducer Channel sensor and set desired value to one Transducer Channel actuator from program for aerometric system. Program for ADC was tested on IEEE 1451 demo board [12] because of its easier replacement. IEEE demo board and ADC are shown in Fig. 10.

Captured communication between TIM module, running on demo board, and NCAP module on PC over serial line (serial line contains only transferred data, thus is more suitable for displaying than CAN) is shown in Fig. 11.



a) b)

Fig. 10: a) Air Data Computer, taken from [13], b) IEEE 1451 demo board.

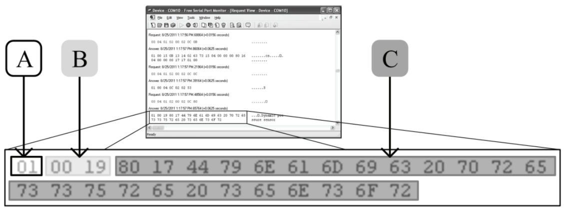


Fig. 11: Communication between TIM and NCAP modules.

Communication was captured in Free Serial Port Monitor [14]. Highlighted area shows response packet from TIM module in hexadecimal format, part A contains success flag, part B contains length of data and data in part C contains identifier (80), length of text data (17) and text “Dynamic pressure sensor” in ASCII code.

We can compare smart sensor supporting group of standards IEEE 1451 and without this support with focus on speed of reading data from device. We measured time from sending command packet over CAN bus to receive answer from device. Measurement was held on the same demo board with different firmware. Communication speed of CAN bus was 1 MBd. Results of this measurement are in Fig 12. Smart sensor which supports group of standards IEEE 1451 has higher reaction time, which is caused by higher complexity of command packet recognition in TIM module. Still the speed of module TIM is almost the same as the speed of module without TIM support.

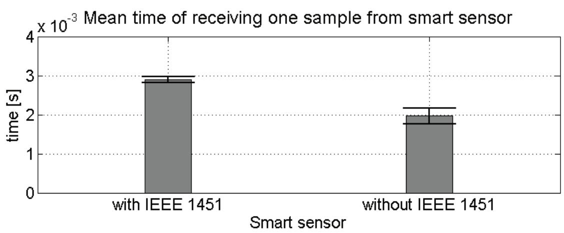


Fig. 12: Communication between TIM and NCAP modules.

Conclusion

This implementation of a group of standards IEEE 1451 in an embedded device increases the microprocessor’s load and extends its average response time for 1 ms. On the other hand this value is negligible within modern and powerful microcontroller systems where the IEEE 1451 group of standards brings more benefits than drawbacks.

The multiplatform library created in this work serves as an integral part of NCAP and TIM modules simulated on a PC platform but it can be used also in any embedded system programmed in C language. This library can store all the TEDS memory data sets, which are defined in one xml file. NCAP and TIM modules can communicate with each other by a serial line, the TCP/IP protocol and the CAN bus. A wireless communication between modules will be added in future. The results described in this paper forms fundamental elements for future aircraft networks composed from distributed sensors and actuators, which will be able to describe themselves. The multiplatform library was used in an ADC and can be used in other embedded systems, e.g. system for position angles measurement or suspended probe for altimeters calibration.

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