A dynamic sensor interpreter for robotic systems

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Abstract*— Changing configurations of robots e.g. in modular robotics, due to retrofitting or maintenance often requires the addition of new sensors that are previously unknown to the system. Usually, it takes quite some effort for the logical integration until the sensor data can actually be used in the system, like updates of the host software, installing drivers or software modules. This can be a time consuming and potentially also an error-prone task. We propose an approach to speed up this process by including an electronic data-sheet standard in the sensor node that contains meta information such as the physical quantity that is measured, the encoding of the data, data rate, calibration data or measurement uncertainty. Based on this information, a Network Capable Application Processor (NCAP) on the host side can automatically integrate the device in the system by adding the information to a so-called parameter server and providing the sensor data (including calibration) as Robot Operating System (ROS) topics. It is important to note that this procedure does not require any change of the software on the host side. Furthermore, the data-sheet also allows to validate if a certain sensor suffices the requirements for a certain task, which is of particular interest in modular approaches, where configuration are frequently changed over the lifetime of the system. Consequently, the proposed approach not only helps to speed up the integration of new devices but also contributes to the stability of the system as automation reduces the risk of errors and as avoidance of additional software modules and drivers reduces the risk of incompatibilities. We demonstrate the benefits of the approach in the retrofitting of a forestry crane with sensors. With the addition of such sensors, such machines turn into autonomous systems enabling the automation e.g. of ordering wood logs.

I. INTRODUCTION

Modern robotic systems rely on massive amounts of sensing devices such as vision-based sensors, tactile sensors, time-of-flight sensors or near-field based methods to perceive their surrounding and interact with the physical world [1], [2], [3], [4]. Often, existing robotic platforms are equipped with new sensors, previously unknown to the overall system. The integration leads to time consuming tasks such as software updates, adjustment of code or re-calibration. Also, potential errors in the software may occur, which leads to further integration cycles. To ease such tasks, the IEEE 21450 standard family has been developed for transducers in various sensing applications. An important field of wireless and smart transducers is in the field of robotics, where autonomous agents are equipped with multiple different sensing modalities. Hence, each sensor transmits data in a different structure and contains different information such as calibration data or sensor-specific metrics. The electronic data-sheet Transducer Electronic Data-Sheet (TEDS) defined in the IEEE standards provides descriptions of sensor channels in terms of physical quantities, data representation, measurement range, uncertainty or calibration data. Consequently, such electronic data-sheets can be seen as a specification of a device and might therefore already be conceptually developed in an early design phase. A short introduction to the standard IEEE 21450 is given in [5], [6]. An example implementation of TEDS is shown in [7] and an example of using TEDS to connect multiple sensor nodes is shown in [8]. We propose to implement the methodology of TEDS into a robotic framework composed of multiple different sensors. The NCAP acts as a central component in the system and the TEDS as a means for supporting easy connectivity and documentation of a smart sensing devices. To showcase the benefits of this approach, we investigated a forestry crane as a use case example, which is retrofitted with a number of sensors. Usually, such systems are operated by humans and do not exhibit autonomous behavior. Using the sensory information on the forestry crane, autonomous sorting of wood logs (see Fig. 1) can be achieved by implementing e.g. a closed-loop control. The integration procedure is explicitly shown for a sensor, as representative for any sensor, which retrieves the angular position of the crane rotator to support the overall control architecture of the crane. The angular sensor information is crucial for the system to align the

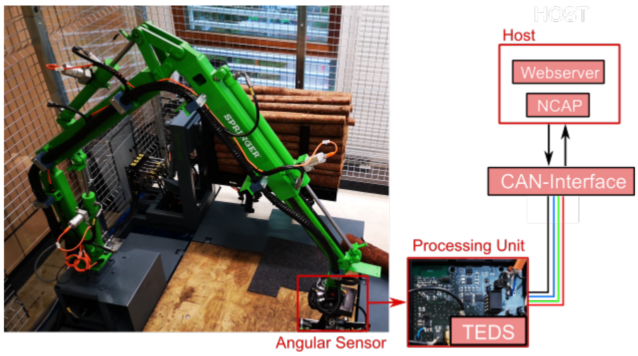

Fig. 1. Illustration of the implementation of the proposed approach on an automated crane system. The host communicates via CAN bus to a processing unit where the TEDS of the sensor is implemented. Data from the sensor is retrieved and processed in the processing unit composed of a microcontroller and sent via CAN to the host.

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altitude of the grasper with the pose of the wood log for successful grasping. An important aspect of these sensors is the possibility to retrofit them on different shaft diameters on different robot platforms. Hence, forestry cranes of different scale can easily be equipped with the same sensor type. This leads to different calibration data for every scenario where the sensor is deployed. Hence, with an architecture as given by the TEDS, the integration of these sensors in new systems including the corresponding calibration information is simplified. In the proposed network, the sensor gets connected to the NCAP via a wired CAN interface to send and receive data. Furthermore, our framework also integrates direct connection to the well-known ROS which streams all sensor information as ROS topics. Besides pure sensor data, the node also includes the calibration information of the sensing device and sensor-specific data such as the CAN ID of the sensor node. The proposed procedure enables a unified, fast and dynamic connection procedure for transducers used in the robotics domain to the network and ROS. Finally, with the proposed approach it is possible to use and deploy transducers on different robotic platforms with minimized effort which potentially speeds-up the integration process into existing systems.

II. System Architecture

A. Prototyping System

The robotic system under examination is a hydraulic actuated industrial log-grasping crane. The crane is a 1:5 laboratory model of a crane employed at sawmills. Its total arm length is about 2.5 m. The crane-arm comes with two rotational joints, one at its base and one at the end-effector, and 3 linear joints as well as actuation of the grasper. Apart of its size, the log-crane does not differ from a state-of-the-art real-world crane. Fig. 1 shows the laboratory forestry crane model. Initially, the crane is only equipped with hydraulic pressure sensors to detect leakage and over-pressure situations. The crane is manually controlled by humans and autonomous acting of any kind is not possible. Engineers strive to automate such systems which may work well without a human operator to increase productivity while decreasing operational workforce. The basis of autonomous acting is sensory information about joint states and the environment. Therefore, the crane is retrofitted with a number of sensor, i.e. cameras, inertial measurement devices as well as linear- and rotational position sensors. Bowden sensors are used to measure the linear displacement of the translation joints. For the rotational joints, off-the-shelf sensor systems do not fit, because usable space for sensors is very limited which is visualized in Fig. 2. The figure shows a self-developed absolute angular position sensor which measures angular displacement of a rotational shaft with respect to a static mounting. The rotational shafts of the different revolute joints have different diameters, i.e. 40 mm and 70 mm. However, the sensor design for one joint can be scaled to be applicable for the second joint. The self-developed angular position sensor is described and extensively analysed in [9] including an automatic design procedure applicable

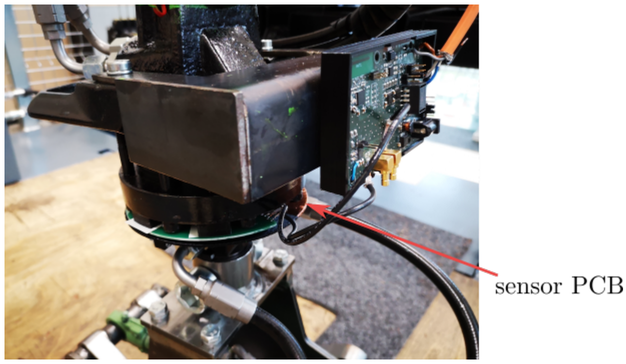

Fig. 2. The exemplary angular position sensor mounted on the limited space at the crane rotator is shown. The custom made sensor requires calibration, synchronization and validation of its provided raw-data before being supportive to autonomous log grasping (angular alignment of log and grasper).

for various geometries. The pure scaling of the sensor introduces measurement errors which can be corrected by means of calibration. Consequently, a number of those sensor require a number of unique calibration sets which introduces management overhead. To simplify this, the calibration data is stored in the electronic data-sheet of the individual sensor. Throughout this paper, the angular position sensor at the end-effector of the crane with the 40 mm shaft is used. For completeness, the key properties of the sensor are summarized in Tab. I. The presented properties are achieved after calibrating and post-processing the sensor output. Additionally, the communication to the sensor needs to be established and synchronized. Commonly, this is done by the user of the sensor which may also use a great number of other sensors leading to a complex and time-consuming task. This paper proposes an automated integration process of sensors and provides a common interface to the measurement data. The angular position sensor under exam is taken to showcase the benefits of the approach. The following parameters are stored in the electronic data-sheet of the angular position sensor: information about the measured quantity, uncertainty information, a look-up table for calibration, an adjustable sensor offset and the update rate of the sensor. Note, that the data is specific to any individual sensor. Especially, when including multiple sensors to a system it is convenient that the sensor specific data is stored in each sensor individually. The following sections explain how the stored data-sheet is used in a generic fashion.

B. Universal Sensor Integration

The physical sensor interface is completed by a number of functional blocks to ease the access and usage of the generated data. A schematic overview of the used blocks and their links is shown in Fig. 3. In the following paragraph

TABLE I
Properties of the custom-made angular position sensor.

Range	Absolute Accuracy	std. Deviation	Update Rate
360°	1°	0.4619°	10 kHz

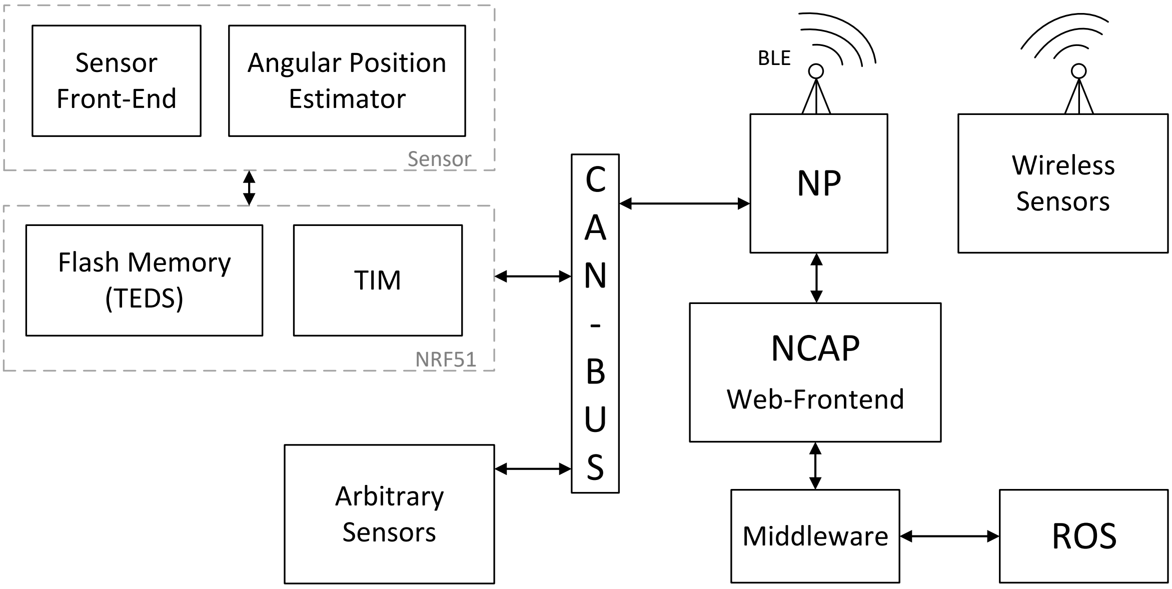

Fig. 3. A schematic overview showing the individual functional blocks of the angular position measurement system integrated in the proposed sensor interpreter system is reported.

the functionality of each block is explained in detail. The actual sensor is comprised by an induction coil front-end and electronics components which estimate the absolute angular position by means of decoding spatially modulated induction data. The angle estimate is then encoded and forwarded as analog voltage which is sampled by the Analog-to-Digital Converter (ADC) of a micro-controller, i.e. NRF51422. The electronic data-sheet, which describes the functionality of the sensor is stored inside the flash memory of the microcontroller. The electronic data-sheet is stored in the ISO/IEC/IEEE 21450 TEDS standard format. The overall sensor board including the micro-controller and bus interface, or so-called Transducer Interface Module (TIM) is connected to a CAN bus which is a common network structure in industrial robotics. A dedicated transceiver Integrated Circuit (IC) is used to translate information provided by the micro-controller as well as voltage levels to CAN messages. Besides the CAN also other interfaces can be used with the proposed approach, e.g. serial interfaces or wireless connections such as Bluetooth Low Energy (BLE). On the base-station side of the system, a Network Processor (NP) is used to connect to the TIM. The NP comprises all physical communication channels. Wireless approaches with optional energy harvesting would enable placement of the transducer in positions which could be constrained by space or moving parts, so that cable connections would not be possible [10]. For each provided interface, a NP negotiates the connection, and provides the decoded commands and measurement values via e.g. a Universal Asynchronous Receiver Transmitter (UART) interface to the base-station or NCAP. The NCAP handles all connected transducers and provides a basic command interface, which every connected transducer can interpret. These commands include the possibility to read a TEDS stored in the flash memory of a transducer, write a new/overwrite the TEDS of a transducer and to switch between transducer modes. Offered modes are, firstly, a measurement mode where the interface is optimized for measurement data streaming from the transducer, and secondly, a configuration mode where the interface is optimized for bi-directional transmission of commands and possible exchange of security information like asymmetric keys, which could be used to secure a system and establish trust between base-station and transducers. Such a security approach is proposed and implemented in [11]. The NCAP can be controlled either via an Application Programming Interface (API) or from a web interface which provides an overview of the connected transducers and enables access to the provided functionalities. The NCAP is able to establish and manage transducer groups, where multiple transducers are grouped together by their Universally Unique Identifier (UUID). The transducers of a group can be a controlled at once, e.g. the entire group of linear position sensor should switch to measurement mode. When the transducer switches to measurement mode it passes the stored TEDS to the NCAP before it starts to publish actual measurements. The NCAP uses the meta-data of the received TEDS to modify the input data stream, e.g. calibration and retrieval of physical quantities of the raw data. Afterwards, it hands the data over to the middle-ware block. At the current stage two different kind of middle-wares are supported: raw-text files and ROS connection. In the crane scenario, after processing, the data is published to the ROS system as an pre-defined ROS topic. In addition, also meta-information (data stored in TEDS) about the node can be requested as a ROS topic.

The NCAP manages the namespace of ROS topics, which can be controlled via the NCAP's API or web-interface.

Additionally, the NCAP also offers the possibility to change the detection mode of new transducers in the system. It can either detect and include all available transducers, or it is restricted to transducers listed in a white-list. The white-list is implemented as Extensible Markup Language (XML) file containing the UUID of the individual transducers. Generally, the transducer may well also be an actuator instead of a sensors or a combination of both. Therefore, the NCAP provides the functionality to send values in the correct format according to the used actuator. During sensor development process it may be of interest to integrate a sensor simulation in the entire framework, i.e. its target application. The NCAP provides the option to create a virtual transducer from a supplied electronic data-sheet. The raw data for this virtual sensor is supplied by the underlying sensor simulation, e.g. physical sensor simulation. Both virtual and real transducers publish ROS topics in the same format.

C. *Electronic Data-sheet*

The electronic data-sheet standard used in this work is the ISO/IEC/IEEE 21450 TEDS standard. Electronic data-sheets in this standard, store different information about the transducer but also have inherent safety mechanisms such as check-sums. For the robotic application (crane scenario) the used technical features of the TEDS are explained in the following. The data-sheet is structured in three fixed and one optional part. The first fixed part are the meta information. Meta information are the number of channels of the transducer, the UUID of the transducer, the transducer type and information about power consumption. Secondly, the channel section is comprised of the number of data bits and the physical quantity to be measured. This is stored for each channel of the transducer. Thirdly, the calibration part explains the calibration procedure. Here, either linear, polynomial or look-up table based calibration can be performed and the according coefficients are stored in the data-sheet. Optionally, text-fields to name channels and the transducer can be added to simplify identification in the system.

D. *Use Case*

The retrofitted sensors of the forest crane are logically integrated using the proposed approach. As an example, the implementation of the approach is shown for a transducer mounted on the rotator of the crane which acts as a sensing unit of the absolute angular position. To show the functionality, an electronic data-sheet was created consisting of one channel. The data streamed via this channel is the raw measurement value of the angular position encoded by a 16 bit data format. Also, the calibration information in form of a look-up table is included in the electronic data-sheet. First, the NCAP identifies the transducer and loads the TEDS from the angular position sensor. Once this is done, the raw measurement values sent by the sensor are calibrated in the NCAP and the processed data is automatically published to a ROS topic. The web interface of the implemented NCAP for this use case scenario is shown in Figure 4. The web interface with the selected angular position sensor is shown. It consists of the core functionalities such as reading and writing to the TEDS and changing the mode of the transducer via the *Configure Transducer* field. After startup, the angular position sensor is automatically set to measurement mode in order to be used by the control architecture which subscribes to the ROS topics of the system. The main advantage of the proposed approach is that the control unit does not need to care about sensing modalities. Especially when a high number of sensors is used, this simplifies the control system architecture.

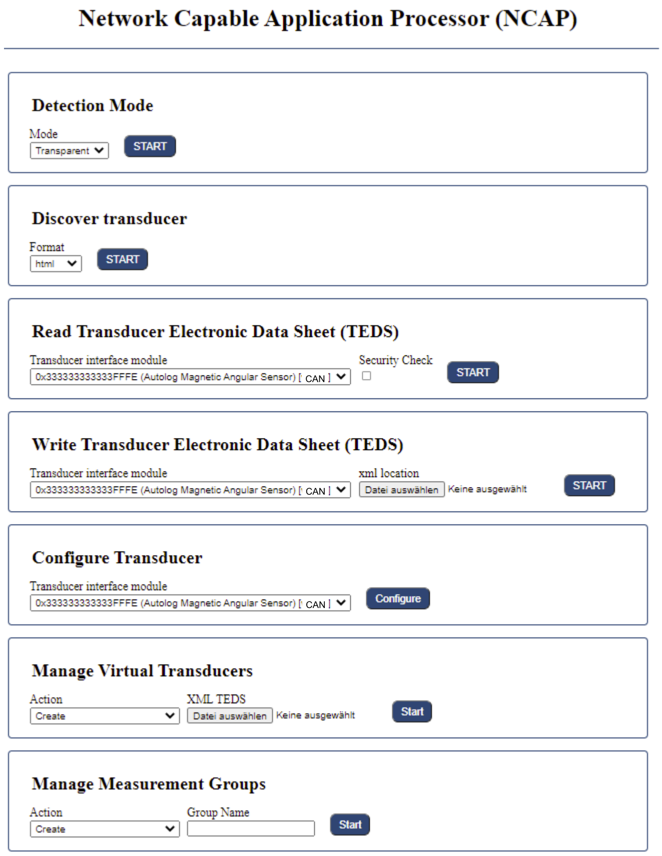

Fig. 4. Overview of the NCAP web interface with the NCAP functionalities.

E. *Discussion*

The proposed system is able to identify, logically integrate and use new sensors containing a electronic data-sheet, to the overall system. In the case of custom made solutions, i.e. the angular position sensor under examination, it is possible to consider the required storage for the electronic data-sheet during design. In the case of commercial sensor solutions the possibility to store the data-sheet is often not provided. However, for critical sensor systems, e.g. sensors which change their characteristic over time (aging), it is possible to logically wrap a micro-controller environment around the sensor. The micro-controller environment serves as an interface to the proposed sensor interpreter system and it contains the data-sheet. Although, this implies some efforts to be done. Ideally, the manufacturer of the sensor would provide an pre-stored and also changeable electronic data-sheet along with the sensor. If the sensor manufacturer complies with IEEE standards, it is very easy for developers to use and modify the data-sheet information with the proposed approach.

III. SUMMARY AND OUTLOOK

In this paper an approach to automatically integrate sensors is presented. In contrast to the common scenario of logically implementing a sensor, i.e. installing drivers/software modules and writing individual code for the encoding, calibration and synchronization of the data, used sensors are automatically integrated and offer already conditioned data. This is achieved by storing meta information about the sensor in the respective sensor itself and automatically downloading this electronic data-sheet when the sensor is physically integrated in the network. Based on the data-sheet information, a network capable application processor on the network host can automatically integrate the device in the system by adding the information to the parameter server and providing the sensor data (including calibration) as ROS topics. This does not require any change of the software on the host side. In addition, the data-sheet can also include a security section, that can be used e.g. to validate the trustworthiness of the component, the trustworthiness of the calibration and to secure the communication. The benefits of the approach are demonstrated on the example of a realistic 1:5 laboratory model of a hydraulic forestry crane. The forestry crane is retrofitted with various sensor to perceive the environment and estimate joint states, to ultimately be used for autonomous acting, e.g. the ordering of wood logs. The variety of sensors measure different physical quantities and have different meta parameters which makes the correct handling of the sensors a complex task. The dynamic sensor integration of the proposed approach speeds this process up and ensures that following control algorithms get valid, correct, and synchronized data.

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