A Solution to the Generalized ROS Hardware IO Problem – A Generic Modbus/TCP Device Driver for PLCs, Sensors and Actuators

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Abstract—The Robot Operating System (ROS) provides a software framework, and ecosystem of knowledge and community supplied resources to rapidly develop and prototype intelligent robotics applications. By standardizing communication, configuration and invocation of software modules, ROS facilitates reuse of device-driver and algorithm implementations. Using existing implementations of functionality allows users to assemble their robotics application from tested and known-good capabilities. Despite the efforts of the ROS-Industrial consortium and projects like ROSIN to bring ROS to industrial applications and integrate industrial hardware, we observe a lack of options to generically integrate basic physical IO. In this work we lay out and provide a solution to this problem by implementing a generic Modbus/TCP device driver for ROS.

I. INTRODUCTION

The Robot Operating System (ROS) is a meta-operating system for robots. It shall provide users with "hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management" [1]. Supplied by either ROS itself, or as community supplied resources. By building an ecosystem of knowledge and supplemental community supplied software resources, it allows to rapidly assemble and prototype intelligent robotics applications. By standardizing communication, configuration and invocation of software modules, ROS facilitates reuse of device-drivers, algorithm implementations and tooling. Using existing implementations allow users to assemble their robotics application from tested and known-good capabilities.

ROS has a strong focus on service-robotics and intelligent autonomous mobile robotics application, providing out-of-the-box solutions to common high level problems like e.g. path-planning, navigation and execution of (mostly) wheeled locomotion, using the navigation stack [2], as well as trajectory planning and execution for multi-axis manipulators and grippers using MoveIT [3]. These high level solutions are complemented by sensor-drivers, enabling the necessary perception for the planning tasks and subsequent execution. Founded in 2012, and supported by projects like ROSIN [4], the ROS-Industrial [5] consortium aims to bring ROS to industrial applications and integrate industrial hardware into the ROS ecosystem. Industrial applications, especially automation in production and handling, are starkly characterized by their interaction with and physical manipulation of the real world. Thus, for a successful application of ROS in industrial application, there exists a strong demand for integration of actuators and sensors of different modalities.

Even tough these components are readily available, and usually implement well defined and standardized interfaces, we observe a lack of options to integrate this wealth of existing sensors and actuators from (not limited to, but especially) industrial applications into the ROS environment in a generic way. This deficiency is as far ranging, as the integration of a simple button or switch poses a serious hurdle in ROS application development. To our knowledge, no solution to this broader problem, providing IO integration with sufficient scalability, portability and flexibility, exist within the ROS ecosystem today.

With the following work we want to show a way, and provide the accompanying tools (software), we deem an acceptable solution to the problem stated above; in industrial, as well as research and hobbyist applications.

II. HARDWARE DRIVERS IN ROS

Reviewing the official ROS community resources [6] and [7], the ROS industrial resources [8], as well as publicly available projects on [9], we identify five main categories of drivers:

1) 2D vision sensors (cameras)
2) 1D - 3D depth sensors: mostly LiDAR, ToF and stereo-vision
3) Robotic arms/manipulators
4) Vendor specific "robotics" platforms

1We abstain from providing a (exemplary) list of reviewed driver, as we are neither conducting a systematic review, nor do we believe that a - under all circumstances non-exhaustive - list would be of particular benefit to the reader
5) *non-ROS-enabled* wrappers for (field bus) communication protocol implementations

The last category mostly just wraps libraries for ROSs’ dependency management and build system (*catkin*) and is of no further interest here.

We can further classify the first *four* driver categories by the following properties:

- A well defined hardware-interfaces with same semantic output (data class) and small variable-parameter-vector
- B high market penetration of targeted hardware, or low availability of competitive products

Where an example for category A would be the *usb_cam* driver [10], providing an interface from *v4l/v4l2* (Video for Linux (2)) compatible cameras to ROSs’ standardized sensor_msgs/Image format. Category B would be covered by (mostly) vendor specific drivers for e.g. LiDAR-Scanners, like SICK (cmp. [11]), or Intel Realsense depth cameras (cmp. [12]). The two categories are non-exclusive though: Common drivers for each (most) all e.g. *ABB* or *Universal Robots* industrial robotic arms (cmp. [13], [14]), or *iDS uEye* cameras (cmp. [15]), fit both categories.

The first category poses a high incentive for the community and community developed drivers, as standardized interfaces usually increase the available options and this decrease the price; ultimately increasing availability and accessibility. The second category allows for two driving mechanism in driver development: First, manufacturers targeting the ROS community as a market. Second, a demand for specific sensor modality or properties, driven by the community.

ROS has ever been targeting *NIX based computer platforms in general, and the Ubuntu platform in particular [16]. It is thus not surprising to observe another common property across the available ROS drivers:

- ROS drivers target Hardware with interfaces commonly found on general purpose computing platforms, e.g. Universal Serial Bus (USB), serial COM interfaces (RS232/RS485/UART) or Ethernet connections.

### III. Problem Statement

**Basic** industrial IO components (sensors and actuators) usually expose their functionality as one input or output per individual function; either logic/digital (on/off) or analog (continuous range of values). These interfaces adhere to the basic specifications of \( \{5V, 10V, 24V\} \) for digital and logic IO, and voltage and current signal in the ranges of \( \{10V, 10V\} \) and \( \{4mA, 20mA\} \) for analog signals as defined by [17], [18].

When comparing the above mentioned interfaces to property C of available ROS drivers, we can immediately observe a problem:

> Recent general purpose computing platforms do not provide individual connections for general purpose logic or analog signal inputs.

For common IO components or simple applications like switch/contact readout, we can further imagine property B to not be fulfilled. Applying the abstraction of all functionality to the two generic interface modalities, logic IO for discrete binary states, and analog IO for the representation of a closed continuous interval of values, it is trivial to see property A to not apply in this case as well.

The lack of physical interfaces on current computing platforms poses a serious technical hurdle to the implementation of ROS drivers for sensors and actuators; without additional hardware and specifications, an integration is impossible. The lack of a ubiquitously available hardware interface, and knowing property A to not apply, further lowers the interest of the community to drive a generic driver development.

To provide a solution to the *generalized problem* of a flexible, portable and scalable hardware IO integration into the ROS ecosystem, we first need to identify a set or class of possible hardware interfaces providing the necessary general purpose IO (GPIO) capabilities, a common communications protocol to mediate between hardware and software layer, and subsequently define and implement a generalized software abstraction on top of its concepts. The general structure of which is show in fig. 1.

### IV. Choosing a Hardware Interface and Communications Protocol

Providing general purpose IO capability and transferring acquired data or accepting setpoint values over a standardized communications protocol is a common application in industrial automation system. Vendors like e.g. *Beckhoff*, *Wago* and *Phoenix Contact*, provide bus couplers for all major industrial communication protocols and busses. These devices themselves are then expandable in their IO capabilities by adding additional IO-modules; the same applies to PLCs. Bus coupler and PLC manufacturers usually provide a wealth of IO modules for their respective platform, enabling sufficiently *general purpose* IO in respect to the problem at hand. Consequently, for the remaining part of the work, we will assume the device-class of bus couplers to be the best representation of a solution to the hardware-facing portion of the overall problem; mapping GPIOs to a standardized protocol. *Further evaluation and selections will be made with bus couplers as the primarily targeted hardware.*

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To provide an as generic as possible solution to the generalized problem, we want the following requirements to be met:

**Scalability:**
- Support hardware interfaces with an extendable IO count; enabling vertical scalability
- Support a scalable number of small (cheap) devices to increase IO count; enabling horizontal scalability

**Portability:**
- Not target one specific device
- Not target vendor-specific hardware or communication protocols
- Prefer technical solutions without the need for specialized communications hardware
- Be hardware-agnostic regarding the hardware platform running ROS
- Shall use commonly available hardware interfaces on the hardware platform running ROS, e.g. USB, serial COM, Ethernet or WiFi

**Flexibility:**
- Provide a single integrated conceptual solution to generic logic and analog IO
- Allow for mapping of hardware/protocol data to basic ROS message types and topic trees

### A. Communications Protocol

Bus couplers and PLCs usually implement fieldbus interfaces. The resulting challenge is the identification of an interface to be used in combination with the hardware running ROS. As analyzed by [19], recent developments of fieldbuses - and communication protocols in industrial applications in general - show an increase in the use of ethernet media access (MAC) and physical layer (PHY). Reviewing the current bus coupler offerings of major manufacturers (as above in section [IV]) we support these findings, while simultaneously identifying Ethernet and RS232/RS485 based solutions as the only commonly available protocols with a suitable PHY. As manufacturers are increasingly adopting ethernet based solution, and serial COM ports are on the decline on recent computer hardware, we rule out the use of serial COM protocols in favor of ethernet based solutions.

The resulting list of commonly available and standardized communication protocols using an ethernet PHY, providing cross-vendor-compatibility, is given as column one of table [I].

Analyzing the properties of the potential candidates, with the help of [19]–[22], we can further compare their benefits and deficiencies and select an optimal solution to our problem. The compared properties and their rating will be made in reference to the satisfaction of our requirements. We identify the following parameters and their associated impacts as a first set of filters relevant to our problem and requirements:

- **Maximum number of devices per protocol;** impacts scalability and portability to existing environments
- **Requirement for special hardware;** impacts portability requirements

| Protocol       | Max. no. Devices | Special Hardware Required |
|----------------|------------------|---------------------------|
| Profinet       | 60               | yes                       |
| EtherNet/IP    | 90               | yes                       |
| Modbus/TCP     | -                | no                        |
| EtherCAT       | 180              | yes                       |
| OPC UA         | -                | no                        |
| MQTT           | -                | no                        |

Table I: Maximum device number and special hardware requirements

With the results, as given in table [I], we can further narrow the selection to the three solutions not capping the maximum number and not requiring special hardware for operations.

1) **Protocol Overview:** Properties of the three remaining contenders will be described briefly; focusing on conceptual differences and feature set, as well as a short analysis on the availability of protocol implementations in suitable hardware devices.

**OPC UA:** The OPC Unified Architecture defines a layered architecture for communications between devices [23]. While the specification mostly defines concepts and behaviors, standardized mappings ([24]) to concrete technical implementations exist and provide the flexibility to choose the application specific optimal technologies. At its core, OPC UA specifies a methodology for information modelling, specified in [25]. With this information model, OPC UA allows to describe, among other information, the available data/variables to be read from and written to a server (device), modelling e.g. hierarchical relationships and annotating values with datatype, physical unit and a (unique) name/identifier. Providing a descriptive information model of the provided data is a highly desirable trait of the OPC UA communication stack, as it allows for automatic and dynamic configuration of a driver (or client in general) from the devices' information model.

Implementations of OPC UA servers are commonly available in recent PLCs. Reviewing the functionality of implementations provided by Wago, Beckhoff and Siemens, we find that only variables present in a PLC program may be exposed over OPC UA. No direct access to IO modules attached to the PLC is possible via OPC UA without mapping these to a variable. While OPC UA server support in PLCs seems in place, reviewing the OPC foundations' list of certified products [26], we identify only a single device [2] implementing bus coupler like behavior and exposing its attached IO modules directly via OPC UA.

**MQTT:** The Message Queuing Telemetry Transport (MQTT) [27] provides means of network communication built on the TCP/IP stack, targeted at IoT applications. MQTT is a pure transport and messaging implementation and does not define payload data serialization. Without a standardized and

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widely adopted serialization, MQTT alone cannot ever satisfy our requirement for flexibility. Sparkplug [28] is a specification for topic organization of the MQTT publish-subscribe architecture and serialization of MQTT payloads, intended to provide compatibility of devices and applications in industrial IoT (IIoT) applications. Sparkplug provides means to discover device capabilities and provided data, as well as device/node discovery on the network.

While MQTT alone and in conjunction with Sparkplug seem to provide a desirable performance over competing protocols (cmp. [21], [22]) we are unable to identify a serious number of devices implementing Sparkplug.

For the remainder of this work, MQTT will be used to refer to the combination of MQTT and Sparkplug.

Modbus/TCP: Modbus/TCP, at its core, allows to call defined methods on a remote device and receive the corresponding function call result. Methods for data access build on the Modbus data model; both specified by [29]. This basic data model distinguishes between bit and register values, while methods for read and write operation for each singular or multiple of these values are provided. While Modbus does not provide any standardized means to communicate meta information like data type or physical unit, Modbus/TCP enabled devices commonly adhere to the data types specified by IEC-61131-3 [30].

Apart from specialized Modbus/TCP-bus couplers, virtually all PLCs and bus couplers with an ethernet connection provide a Modbus/TCP server/slave implementation. Modern PLCs using a IEC-61131-3 compatible runtime, without a vendor supplied server, may add Modbus/TCP compatibility as a software package/module [31].

2) Protocol Selection: As all three protocols are publicly available and open standards, and are either based on – or provide capability to leverage – standard ethernet based communications, we assume all three to directly satisfy all but our first requirements in regards to portability. Further, all protocols do support transmission of individual data points and types for representation of analog and digital IO, thus satisfying our requirements in relation to flexibility.

MQTT and OPC UA, each seem to provide technically optimal solution to the integration and exchange of IO information with hardware acquisition devices, for the problem at hand. Both provide bidirectional data transmission, either explicit or implicit discovery mechanisms, and data typing. The goal of providing an actually applicable solution, prohibits the evaluation of communication protocols independently of the availability of suitable hardware. The fulfillment of our requirements relating to scalability is tightly coupled to hardware availability, and cost/simplicity of protocol implementation on devices to enable horizontal scalability.

Based on the analysis of available implementations in hardware, we conclude that neither OPC UA nor MQTT are sufficiently supported by available hardware. While OPC UA has good support on PLCs, support in bus couplers – as object of consideration (compare section IV) – is negligible. The overall support of MQTT is considered negligible as well. The low number of hardware options supporting vertical scalability, makes both OPC UA and MQTT not fulfill our first requirement of portability and thus effectively not satisfying the requirement of vertical scalability itself. Modbus/TCP, on the other hand, constitutes a technically inferior solution, while showing significantly higher adoption and availability of supported hardware, thus fulfilling the requirements of portability and vertical scalability. The fitness for horizontal scalability, usually enabled by low cost – commonly implying low resources – of supporting devices, can be assumed to be inversely proportional to the complexity of a technology. Assessing each protocols complexity in comparison to each other, we can establish following order from least complex to most: Modbus/TCP, MQTT, OPC UA. Using this scale as an indicator for horizontal scalability, Modbus/TCP constitutes the preferred choice.

Based on the above evaluation, we identify Modbus/TCP as the currently optimal solution to our problem, and choose it as the common denominator for integrating hardware IO with current general purpose computing hardware running ROS.

As its core functionality, Modbus/TCP allows read and write access to memory regions – usually representing IO states or program variables – on a device. While not specifying data types and being able to deduce the data type from register data itself, most Modbus/TCP enabled devices adhere to the data types specified by IEC-61131-3. While the nature of Modbus/TCP requires the specification of addresses to be polled for data, thus demanding additional efforts for configuration, this property allows to map these individually requested values to ROS topics with a specified data type.

Being an old protocol, in comparison to its contestants, Modbus/TCP still has wide support - not limited to industrial applications. Internet of Things (IoT) cloud solution providers like Microsoft Azure [32], AWS IoT SiteWise [33] or Alibaba Link IoT Edge [34], support data integration for Modbus/TCP devices.

B. Hardware Compatibility Consideration

Our requirements for portability forbid the selection of specific hardware devices. Consequently the hardware interface is represented by a class of devices implementing our chosen communications protocol.

The simplicity of the Modbus/TCP protocol and its foundation on the TCP/IP protocol stack allow for good compatibility across a wide range of platforms. As support and availability of implementations in PLCs and bus couplers has been the driving factor in the protocol selection, compatibility for these classes of devices is granted.

For horizontal scalability, low cost and power IoT devices and hardware platforms provide a solution, while receiving good support for Modbus/TCP compatibility. This class of devices is targeted by operating systems like FreeRTOS [35].
with available ports of Modbus/TCP clients like FreeMODBUS [36], as implemented e.g. by the ESP-IDF (Espressif IoT Development Framework) [37] for the ESP32 System on Chip platform. Bringing Modbus/TCP capability to these low power and low cost microcontroller platforms, increases availability and allows horizontal scalability through low cost.

Generally, all device and operating system combinations providing a TCP/IP protocol stack are able to serve as the base for a Modbus/TCP IO device.

V. IMPLEMENTATION

Despite the listing of Modbus/TCP as a hardware interface protocol in the proposed ROS Industrial roadmap, since at least 2015 [38], [39], there exists no generic implementation of a driver for the ROS ecosystem.

To provide a solution to the generalized IO problem, based on Modbus/TCP, we choose to implement a driver with the following major properties:

- each driver-node instance represents each one slave device or subset of a slaves’ mapped IOs
- each driver with associated mapping uses an individual topic namespace
- map each configured IO to a separate topic
- support read access for discrete inputs and input registers (status registers)
- support read/write access for coils and output registers (holding registers)
- perform data conversion for register data from IEC 61131-3 to ROS std_msgs types (or arrays thereof) and vice versa

The first three properties achieve a separation of concerns in functionality and allow to follow ROS’ ideas of reusability and composition. The remaining properties establish a sufficient base functionality for a generic driver in the targeted domain. Mapping IOs to their own topics each is the best representation of our generic driver approach, while enabling integration of IOs via ROS’s topic remapping functionality.

The driver itself provides an abstraction over one Modbus/TCP device with a selection of mapped IOs. The ROS node holds and manages an instance of a ModbusSlaveDevice, provides configuration and manages ROS publishers and subscriptions (rospy.Publisher and ros.py Subscriber in fig. [4]).

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A. ROS to Modbus/TCP interface

Following, we will give an overview of how the data acquisition process from a slave device to ROS topics, and the process of writing data from a topic to a slave is implemented. For this we will use the simplified and abstracted class relationship diagram from fig. [5] omitting intermediate classes responsible for state management and implementing behaviors not relevant to the overall operation principle. We further want to assume all behavioral differences to be implemented by class inheritance and specialization, while implementing the shown interfaces in fig. [5]. We begin with a brief description of the non-ROS classes, followed by a description of the process for reading and writing data.

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The fetch() method triggers read operations for all RangeReaders.

Mapping: Each input and/or output and its associated topics are represented by a class instance implementing the Mapping interface. Mappings are (for the sake of simplicity, assumed to be) specialized on discrete inputs, input registers, coils and output registers, as well as the type of register data. The decode() method will fetch the registers’ value from a Decoder and call all associated callbacks with the decoded value. Calling write() method will encode the passed data according to type and instantly trigger a write operation to the Modbus/TCP slave.

RangeReader: Aggregates read operations for multiple Mappings to one read operation of a continuous memory region, reducing polling operations and network traffic. Depending on slave behavior, reads from discontinuous memory regions can be aggregated while discarding unmapped memory.

Decoder: Container, owning and representing the raw data returned by a RangeReaders’ read() operation. Implements data decoding functionality from raw data to requested type. Mappings decode their value from the Decoder depending on type.

1) Writing Outputs: The driver node attaches the respective Mappings’ write() method as callback function to a ROS subscriber (rospy.Subscriber) instance for the associated topic. The Mapping class specialization handles encoding of the data in relation to its type and triggers a write operation on the provided ModbusClient instance.

2) Reading/Polling Inputs: Polling a slave is performed by the driver node by calling the ModbusSlaveClients’ fetch() method. This in turn triggers the individual processes described above: Triggering all read() methods of the RangeReaders, which will start the decoding process for all mappings on data reception, in turn leading to a call of the publish() method of the respective rospy.Publisher.

B. Configuration

Creating a device abstraction and mapping its hardware IOs to ROS topics, is accomplished by defining the abstraction as device configuration. The configuration may be supplied in ROSs’ standard configuration file format YAML, or JSON. Assuming a slave with hostname mbdev, Modbus unit 1 and matching IO addresses, we can create a device mapping, representing the example in fig. 2 as in listing 1:

```yaml
name: device
address: mbdev
unit: 1
rate: 20
mapping:
  coils:
    out_2: 1
  discrete_inputs:
    in_A: 10001
  input_registers:
    measure_v:
      address: 30001
      type: LREAL
```

The complete drivers’ implementation can be acquired and studied at [40].

VI. PERFORMANCE ANALYSIS

Translating from ROS messages to Modbus/TCP and vice versa, we will use the time difference between TCP-packets, for ROS messages to Modbus/TCP write-request, and Modbus/TCP read-responses to ROS messages, being available on the network as the relevant performance metric. Read- and write requests from the driver node will be handled by a dummy Modbus/TCP slave, accepting all request and responding with a success-responses, returning 0-values in case of read operations. All data is generated and captured in its own docker container, transferring data over the container internal loopback interface. Each container is running the complete software stack necessary for data acquisition, where n is the number of configured inputs or outputs for the case examined:

- 1 local roscore
- 1 driver node
Experiments yield a $\Delta t_0 = 158\mu s (\sigma = 17\mu s)$ for writing coils, and $\Delta t_0 = 163\mu s (\sigma = 15\mu s)$ for holding registers.

VII. DISCUSSION

By providing a generic implementation of a Modbus/TCP driver for ROS we provide a solution to the generalized IO problem in ROS. While the provided driver only abstracts the workings of the communication protocol and data interpretation (i.e. handling byte and word orders), we believe this to be of great benefit to ROS developers. Using the driver, ROS developers mostly stay in their domain, using high level programming languages on general purpose computers, writing configuration files in standardized formats and interfacing the ROS by use of ROS topics. Mapping individual IOs as individual topics allow for great portability and flexibility while keeping the requirements for the driver low. Adapting topic descriptors to those required by a specific application can easily be achieved using ROS’s remapping methods; thus allowing simple code and application component reuse. Aggregating data from multiple individual IOs to higher level message/data types, conveying semantic information, we consider trivial in the instant all data is available to a developer via ROS topics.

Even though Modbus/TCP may seem like an outdated choice and solution for the problem at hand, it is the most widespread protocol understood by suitable hardware devices, when compared to OPC UA and MQTT as the identified competitors. Modbus/TCP’s simplicity results in good compatibility with a number of devices and allows good horizontal scalability of the solution across devices. With IoT cloud vendors supporting Modbus/TCP (compare section VI-A), we do even expect to see an increase in Modbus/TCP implementations for low cost devices. The simultaneously good support for Modbus/TCP in industrial applications and good availability of bus couplers and compatible PLCs ensures applicability of our solution in industrial applications. This support, combined with the wealth of available IO modules, further ensures a high flexibility in IO choices and rapid prototyping of applications.

The performance evaluation shows the introduction of a time delay $< 0.5 ms$ for the first value of a Modbus/TCP read-request to be available on the ROS network, with subsequent readings of a request being available after $< 0.2 ms$ consistently. In our experience, these values are at least an order of magnitude lower than the response times of actual Modbus/TCP slaves. The performance penalty introduced by the driver is thus assumed to be negligible in ROS applications.

We have successfully used our solution with multiple Wago and Beckhoff PLCs and bus couplers, each with a range of different IO modules. The created IO capabilities have been used to control and read e.g. a robotic gripper, switches and high resolution distance sensors. The integration of each new device being in the range of minutes.

VIII. CONCLUSION

We have delivered the concept and necessary implementation of a solution to the generalized problem of hardware
IO integration into ROS systems. All while delivering a solid rationale for the choice of Modbus/TCP as the underlying technology.

As OPC UA and the combination of MQTT and Sparkplug do provide significant advantages over Modbus/TCP, we expect these technologies to replace a Modbus/TCP based implementation in the future. Building on these technologies allows to reduce configuration to an absolute minimum by leveraging the information model provided by the server in case of OPC UA and the metrics definition of Sparkplug birth certificates respectively.

The main value of this work is seen in the simplicity of the provided tools, and in presenting and delivering the idea, of using standardized industrial protocols to the ROS community; for researchers and hobbyists alike. Being aware of the options available to solve a particular problem and receiving minimal support in terms of tooling, has a great potential for keeping individuals from rolling custom communication protocols over non-scalable communication channels (e.g. using USB/UART and platforms like Arduino as IO hardware), and thus creating solutions adhering to the core idea of ROS: Creating reusable solutions to recurring problems.

Future Work

Future work is expected in the optimization of read and write processes, including batch writing of near-simultaneously published output data, and reducing traffic and load on the Modbus/TCP slave by building dynamic readers and querying subscribed topics only. Further, a notable improvement of the configuration process may be achieved by interpreting the configuration files of Modbus slave simulation and testing tools (e.g. WinModbus [42] or UnSlave [43]).

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