An Open Source IoT Framework for a Distributed Modular Low-cost Laser-based Sensing Platform

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***Abstract*—The transformation of laser-based optical sensors into industrial environments is a time-consuming and costly process, since not only laser safety measures and structural limitations, but also digital infrastructures must be carefully considered. We have therefore developed a modular photonics platform, which is characterized by the possibility of rapid adaptation to individual conditions and is, thus, particularly suitable for agile prototyping. This paper is dedicated to the challenge of implementing a modular Internet of Things (IoT) framework on the basis of existing open source software to offer applicability without a deep background in computer science. The primary approach revolves around the established combination of Node-RED with MQTT. Furthermore, the incorporation of the IoT concept can be seen as a valuable addition in physics. As a first step, we implemented our IoT framework for an initial version of the sensing platform creating the foundation for a basic photoelectric sensor.**

I. Introduction

Today's sensor technology plays a key role in enabling a wide range of users to carry out inspection and quality control in a broad field of different applications. Optical sensors specially tailored to the specific application are used, e.g., in the context of drag reducing riblets in the aircraft industry [6], [17], biological compatibility enhancing coatings used in medical technology [8], [11], or so called conversion coatings in the light metal industry. A state of the art and powerful tool in the development of such optical sensors are specially designed optomechanical components in photonics industries, such as optical tables from *Thorlabs*™ or *Newport*™, required for optical experiments. However, transferring a novel sensor concept from the lab into an industrial product is a lengthy and difficult process that requires cross-disciplinary expertise.

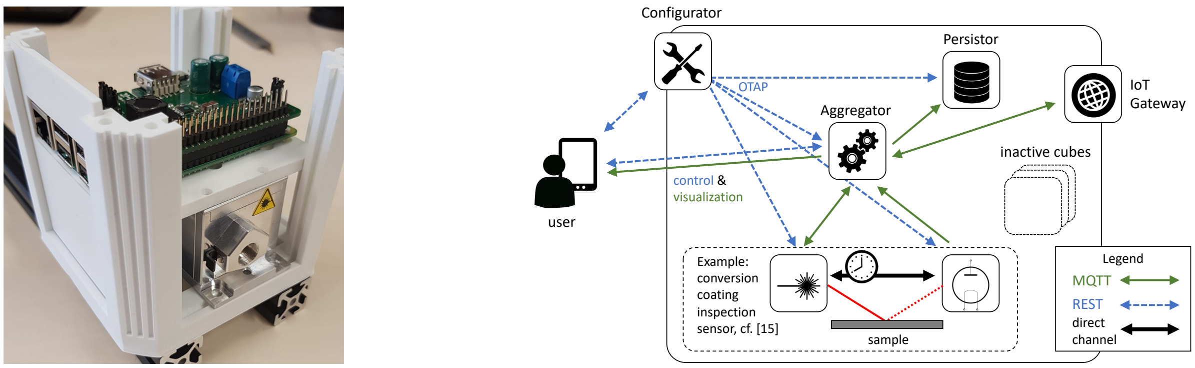
We were involved in the research process of various laser-based sensors, so far, e.g., for the inspection of Cr(VI)-free conversion coatings on light metals driven by the requirement of Europe's REACH agreements 2017 [7]. In particular, we succeeded in the development of a simple physical concept that is capable to validate the quality of ultra thin conversion layers with thicknesses far below 70 nm [15]. However, no attempt to build a prototype has been made, since the transformation of the concept into industry is very challenging taking laser safety regulations, individual requirements for quality control, the integration in the production process, and, in particular, the interconnection with the local IT infrastructure into account. For this reason, the idea to transfer the aspect of diverse applications into a modular and low-cost laser-based sensing platform was born and is mainly subject of this work.

In the context of open source hardware, a similar approach can be found in the μCubes [3] framework providing a basic modular system for optical devices. As key concept serves the modularization of basic optical components that can be produced via 3D-printing technologies. We here present a photonics platform, that is not only open source and 3D-printable, but also can be adopted to the individual needs in the concept of agile prototyping. For this purpose, the platform must provide a convincing solution for mechanical, (photo-)electrical, and hard- and software elements.

This paper focuses primarily on the development of a distributed modular platform and the communication between the individual basic units. The overarching goal is to combine existing open source software to provide a modular Internet of Things (IoT) framework for a laser-based sensing platform in the context of photonics research. Our IoT approach is driven by the goal of developing distributed modules that can be cheaply, easily, and independently manufactured and used. This goal corresponds well with the advantages of the IoT: The easy access to information, the optimized communication over a network of interconnected devices, the cost effectiveness, and the automation of tasks. Our framework enables the basic architecture for a modular laser-based sensing platform. Thus, a rapid prototype for the application in industrial environments can be created and iteratively improved.

II. Background & Related Approaches

Photonics research combined with the IoT has, to the best of our knowledge, not been realized before. However, there are related applications in the industrial domain, e.g., [13], [16]. In both papers, the monitoring and control of industrial structures is implemented as an IoT wrapper on the existing Modbus protocol. The state of the art framework for laboratory control is LabVIEW (National Instruments) [12]. It is a commercially available graphical programming software that controls laboratory equipment directly. However, it is proprietary, expensive, inflexible, and hard to expand due to dedicated hardware drivers. Therefore, we propose to use Node-RED [14] as the open source graphical programming alternative to LabVIEW. It is a front-end for node.js and designed with the IoT in



(a) An example of the developed basic building block, called cube.

(b) Sketch of the implemented system and communication architecture.

Fig. 1. Concept of the IoT framework for a modular laser-based sensing platform.

mind. Node-RED has been utilized before in similar projects like [10], [16], in which it shows fast and effortless connection setups for large numbers of devices. This key feature is needed in our targeted domain to offer applicability without a deep background in computer science.

MQTT [1] is a lightweight messaging protocol. It works well in conjunction with Node-RED. Communication follows the publish/subscribe paradigm and is facilitated by a broker. Clients can subscribe or publish to a message topic. Published messages are then delivered to all clients that have subscribed to this topic. Since this kind of communication is well suited for the IoT, it was also used in several similar projects, e.g., [2], [10], [13]. Here, MQTT is used in two ways: First, devices subscribe to specific topics and can then be controlled by a central Node-RED user interface (UI). Second, sensor data is published to sensor topics and aggregated for processing. In our framework, we use a similar approach to provide a modular backbone network.

III. System Design

A. Hardware Concept

The modularity and the versatility of our sensing platform is achieved by the concept of small, universal building blocks, so-called *cubes*. Their mechanical framework is additively manufactured using low-cost 3D-printing technology. The enclosure is designed for general purposes, cf. Fig. 1(a), offering space for different technical components such as laser emitters and detectors, from simple photodiodes to high-resolution line scan cameras, and also for various mechanical (linear stages, etc.), optomechanical (lens mounts, etc.), and optical components (mirrors, etc.). Low-cost and off-the-shelf single board computers (Raspberry Pi 4) are used as computing and communication hardware components, which can also be battery-powered. A power saving e-ink display shows cube labels and simple software and status information. For data communication, interfaces for various technologies are available, i.e., WLAN, Bluetooth LE, Ethernet, and USB-C.

B. System and Communication Architecture

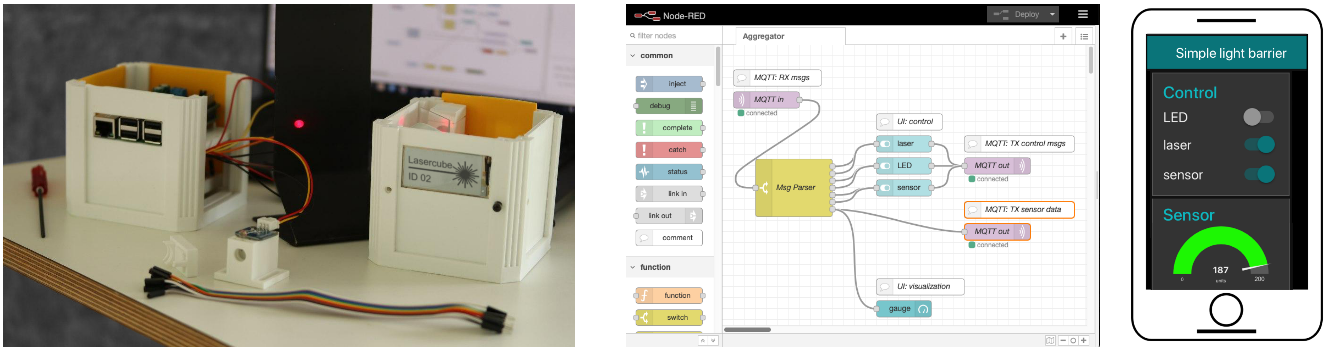
Leveraging IoT concepts, our framework is designed as a modular distributed system of connected cubes. We developed a flexible communication architecture, outlined in Fig. 1(b). A central instance is given by the *Configurator*, a dedicated entity with a web-based UI for a dynamic activation, (re-)configuration, and control of cubes within certain measurement setups. Using the *Configurator*, a user can assign specific tasks to individual cubes: (1) An *Aggregator* serves a managing entity and is responsible for sensor data aggregation. First, it acts as data sink for sensor cubes and, second, it exchanges control messages with actor cubes. Therefore, it also provides a UI to which the user is redirected by the *Configurator*. The UI visualizes (aggregated) sensor data and offers control options. (2) A *Persistor* stores generated sensor and logging information in a data base. (3) An optional *IoT Gateway* integrates the cube framework into the IoT. (4) Sensor and actor cubes that could be equipped with different additional photonics components represent the actual work cubes for conducting physical measurements. Note that several such entities can also be deployed on a single cube.

In the current version, cubes are wirelessly interconnected via a WLAN access point installed at the *Configurator*. We are aware of possible reservations and restrictions of the industry regarding WLAN. In the future, optional wired connections via Ethernet are planned as well. Another aspect that we will address is auto configuration along with the initial registration of cubes. Here, Bluetooth beaconing or QR codes on cubes' displays might be used. Based on the auto configuration, IT security features, e.g., the construction of a public key infrastructure together with TLS [4] are planned.

C. Software Components

The entire IoT framework is strictly based on open source software. It is planed to be made freely available in the future in order to reach a broad group of potential users in both the industry and the developer community. Open source not only decreases the costs of the system, but also makes it very flexible, thus, paves the way for agile prototyping in the domain of photonics. On each single board computer, a standard Linux distribution with a Node-RED instance is used, communicating via MQTT and building a distributed system.

Since Node-RED has many conceptual similarities to LabVIEW, we believe it will increase the acceptance in the photonics community, from a usability perspective. Due to its concept of flows, individual flow-based tasks can be locally



(a) Technical setup of a light barrier (blocked by an obstacle), including the laser cube (right), the detector cube (left) with a photodiode-based sensor (front), and the *Aggregator* (background).

(b) Screenshot of a simple Node-RED flow (*Aggregator*).

(c) Dashboard UI.

Fig. 2. Prototypical realization using the example of a light barrier.

created, easily modified, and also combined with each other at the *Configurator*. An illustrative flow is shown in Fig. 2(b). Using a simple over-the-air programming, which is realized by its REST API, these flows can also be remotely exchanged and deployed on different cubes at run time. Thus, Node-RED significantly increases the needed flexibility and, at the same time, eases the maintainability of software and operational tasks. Whereas REST calls are used for configuration and maintenance, the communication of both control messages and sensor data streams are realized via MQTT. For this purpose, an Eclipse Mosquitto [5] broker is installed on each *Aggregator*. Active cubes are configured to establish connection to a certain broker (as publisher and/or subscriber). If the *Aggregator* is configured to carry out real aggregation tasks, it also executes a flow that subscribes certain topics, processes received data in an appropriate manner, and finally publishes the aggregated data stream for entities at higher layers, e.g, *Persistors* or the *IoT Gateway*.

Moreover, using the default Node-RED dashboard functionality, *Aggregator* cubes can also be responsible for UI purposes, i.e., a basic visualization of state information and sensor data as well as options for controlling experiment equipment of active cubes. If an *IoT Gateway* is available, the *Aggregator* automatically establishes an MQTT connection to a second broker running on this gateway.

Finally, depending on individual demands of specific setups, MQTT links may be insufficient, e.g., in terms of available data rates or real-time requirements, such as low delays. Therefore, special direct communication channels with enhanced capacity and real-time properties are foreseen in the concept, cf. Fig. 1(b). Those single-hop channels are intended to be initiated by Node-RED instances, but internally use more performant programs and hardware-related features of the underlying operating system.

IV. Prototypic Realization

Although a first sensor for conversion coating inspection has already been implemented, we demonstrate our framework by a simple and illustrative laser-based light barrier, for the sake of simplicity. However, this example nevertheless includes the basic features of our framework. Its technical setup consists of two active cubes (laser and detector), which are connected to an *Aggregator* (here also *Configurator*) according to our architecture in Sec. III. This setup is shown in Fig. 2(a).

Using our framework, software development for such a distributed application is not only quite easy due to Node-RED and MQTT, but also very intuitive and compact, as an exemplary program in Fig. 2(b) reveals. The *Aggregator* provides control buttons and a gauge for visualizing sensor data in a dashboard implemented by corresponding nodes (turquoise) in the flow. MQTT endpoints are source or sink nodes (purple) that are simply connected to further nodes, e.g., nodes for parsing incoming messages (yellow). The flows of laser and detector cubes (not shown) additionally contain nodes for controlling the hardware components attached to GPIOs of the Raspberry Pis, namely a laser emitter and LEDs as well as an I2C node for reading sensor data from a photodiode. The interruption of the light barrier is indicated by sensor readings below a certain threshold in a UI gauge, which can be accessed by end-devices, e.g., laptops or smartphones, cf. Fig. 2(c).

V. Conclusion

In this paper, an IoT system and communication architecture was presented, enabling a flexible framework for a modular sensing platform. Based on interconnected sensor cubes, the framework was exemplarily demonstrated by a simple laser-based light barrier as a proof-of-concept. In our future work, we will successively extend our framework by integrating sophisticated sensors, e.g., laser-induced breakdown spectroscopy. Hence, time critical measurements have to be addressed. Therefore, application-tailored mechanism will be developed, e.g., by adapting concepts from [9].

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