The Smart MiniFab: An Industrial IoT Demonstrator Anywhere at Any Time

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Abstract. The fourth industrial revolution is predicted to be one major topic in the upcoming decades, affecting nearly every industrial facility. The key enabler for the successful integration of corresponding developments are well-trained engineers with elaborated knowledge in the area of the *Industrial Internet of Things* (IIoT).

This paper introduces a concept enabling engineering students to gain the required skills for the upcoming challenges connected with the fourth industrial revolution. Therefore, the *Smart MiniFab* was developed - a demonstrator of an industrial facility primed for the implementation and the analysis of different IIoT concepts on a small scale. Due to the modular structure of the system, students can use the demonstrator to programmatically implement the functionality of an entire facility from scratch or to test only certain new concepts. The hardware can be programmed via remote access from anywhere at any time, while live feedback is provided through a webcam and different other communication possibilities directly within the remote access application.

While the Smart MiniFab was already the HW environment of different student projects, a new lab course is currently under development which enables the access to the Smart MiniFab for a broad number of students.

1 Introduction

The intelligent connection of devices, machines, facilities and humans is regarded as the fourth industrial revolution. The main driving forces behind this revolution are known as the *Internet of Things* (IoT) and the *Industrial Internet* (II). While IoT describes the intelligent connection of usually small devices, II specifies the same intelligent connection combined with other smart improvements for larger scale production sites. Both concepts are combined in the *Industrial Internet of Things* (IIoT) which is based on so-called *Cyber-Physical-Systems* (CPS). These systems unite software and hardware to interact with their environment in a smart way. Therefore, they comprise sensors, controllers and actuators on the hardware side and a corresponding controller firmware on the software side. Especially in IIoT scenarios different CPS are interconnected to dynamically control larger production sites so that the overall usage and throughput is optimized. The importance of IIoT for our future in nearly all industrial areas is indicated in different case studies. To give just one example, a survey conducted in 2016 claims that 82% of 173 interviewed companies consider the adaption of IIoT concepts as being critical to their future success [1].

To successfully employ the potential of IIoT, well-trained engineers are essential which not only develop innovative CPS, but also connect and maintain existing or newly created systems. This requires knowledge in the area of mechanics, electronics and computer science as well as a good glance on how to combine these disciplines into the context of IIoT. Especially for the latter this paper presents an innovative concept which aims at the effective training of future engineers with the help of a custom-made industrial facility demonstrator, called *Smart MiniFab*. It was developed at the Faculty of Engineering at the University of Freiburg, where it is used to train engineering students as well as professionals who join qualification seminars. The Smart MiniFab is comprised of different distributed production stations in a small scale, each controlled by a microcontroller and equipped with different communication interfaces. This flexible setup enables either the programming of the entire facility from scratch or the analysis of only certain new IIoT concepts.

To reach as many students as possible we created a web-based remote access to program and interface with the demonstrator. This allows for controlling the Smart MiniFab from anywhere at any time which perfectly adapts to the usually tight schedule of a contemporary student. By further integrating a webcam, different sensors and communication interfaces, this remote access provides an almost perfect live feedback and, therewith, the feeling of "standing right next to the fab".

Based on continuous positive feedback received from students, who have already worked with the Smart MiniFab for team projects, a new lab course is currently under development which will be available to all students at the Faculty of Engineering. Participants of the course will learn the most important aspects connected with IIoT in a very practical way before they start to develop and implement their own project ideas with the Smart MiniFab.

The remainder of the paper is structured as follows: In Section 2 important concepts related to IIoT are introduced. The way they are implemented within the Smart MiniFab is shown in Section 3, together with a general overview of the demonstrator. Section 4 further highlights the individual hardware components of the SMF in more detail, while in Section 5 its remote access is described. Section 6 sketches how the intended lab course will be structured. Related work is presented in Section 7 before the work achieved so far is concluded and links to possible future projects are given in Section 8.

2 Concepts of the Industrial Internet of Things

While the interconnection between different machines and the centralized management of production sites is common today, IIoT introduces new concepts which aim to further boost the productivity and adjust the production to upcoming needs of the market. The most important concepts are briefly introduced in the following:

a) **Decentral Decisions:** One key concept in IIoT is to switch from a centralized production setup to a more decentral model, in which different production machines are allowed to perform their own decisions based on their locally captured (sensor) data, while being at the same time connected to other machines for exchanging global information. When realized in an efficient manner the productivity of the overall production system can be increased. This design shift is also motivated by the fact that the manufacturing process of most products today has moved from one central to multiple distributed locations each performing some sub-steps of the entire manufacturing process [2].
b) **Smart Products:** Closely related to a decentral control flow is the so-called "smart product". The term describes the fact, that the product itself knows how it has to be manufactured and what components or features are needed. This is achieved by equipping a blank product or a product carrier with additional active or passive elements that communicate with the manufacturing machines. An example for a passive element is a QR-code that contains all manufacturing steps and production parameters required for a particular product.
c) **Individual Products:** A common trend on the market heads towards individually designed products. While this is a neat feature for consumers it might be very hard to realize for a company since most existing production sites are typically optimized for high-volume instead of high variability. To enable the production down to "lot size one" IIoT concepts have to be applied such that different products can be manufactured by using the same production machines (in particular without any manual reconfiguration of the machines in between).

3 Overview of the SMF

The Smart MiniFab (also refered to as SMF) is a miniaturized production facility that can handle certain tasks in a smart way. It was build from scratch so that students get in touch with IIoT related hardware without the need to visit external companies or to carry home obtrusive hardware components. An overview of the SMF is presented in Figure 1. It is capable of moving *Tetris* like bricks called tetrominos between different sized containers called palettes. The SMF as one entity is divided into currently three distributed stations **S1**, **S2** and **S3**. S1 handles tetrominos that are asymmetrical in shape since a rotation box allows it to rotate them to a given orientation (see also Figure 3). S2 has no rotation box but features an assembly belt which can move palettes between S1, S2 and S3. Station S3 comprises a WiFi-module and is responsible for handling incoming orders. An order for a "product" can be placed in a web-shop and consists of several tetrominos of different shape, color, and orientation. These are placed at

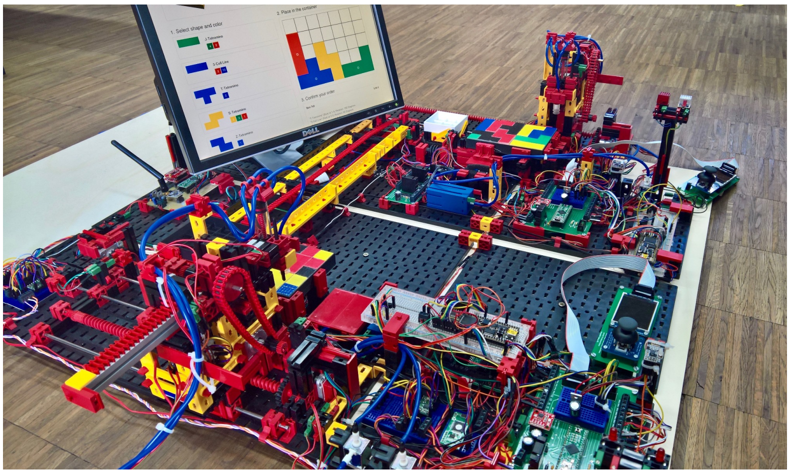

Fig. 1. Overview of the Smart MiniFab.

different positions in different sized palettes. In the context of IIoT the palette can be seen as a blank product which can be equipped with different features - the tetrominos. Currently, eight different tetrominos exist in five different colors and by considering all possible orientations, up to 100 different features are possible. If the different possible positions of the tetrominos inside a palette are also considered, a huge variety of different "products" can be ordered. If such an order is placed, there is a high probability that it is the first time this specific configuration has to be produced. This has a strong relation to the mentioned production in lot size one. Furthermore, the SMF also provides the ability to highlight the concept of smart products since RFID tags with assemble information are attached to the bottom of each palette. Each station has access to the stored information and can start to work on a sub-step independently. To assemble palettes, S1 and S2 both feature an assembly robot which is highlighted in Figure 2. This robot moves along the *x*- and *y-axis*, picking up tetrominos at one position and moving them to other positions where they are laid down. In order to do so, the robots incorporate different electrical components such as stepper motors, end-stops, vacuum pumps and valves together with their corresponding driver electronics.

4 Hardware Components of the SMF

Each station of the SMF features different hardware components that can also be found on large scale production machines. These components collaborate together to perform a given task and, if viewed from a larger scale, to achieve the IIoT concepts introduced in Section 2. An overview of the hardware components of station S1 is shown in Figure 3. For precise movements of the robots along the *x*- and *y-axis* and for the assembly belt of S2, stepper motors are used. Mechanical end-stops determine the end of each axis and are attached to both

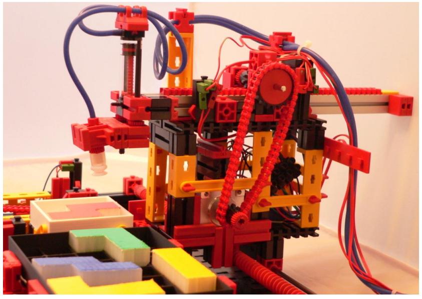

Fig. 2. The robot arm of a station with its pneumatic system and stepper motors for movements in x- and y-direction.

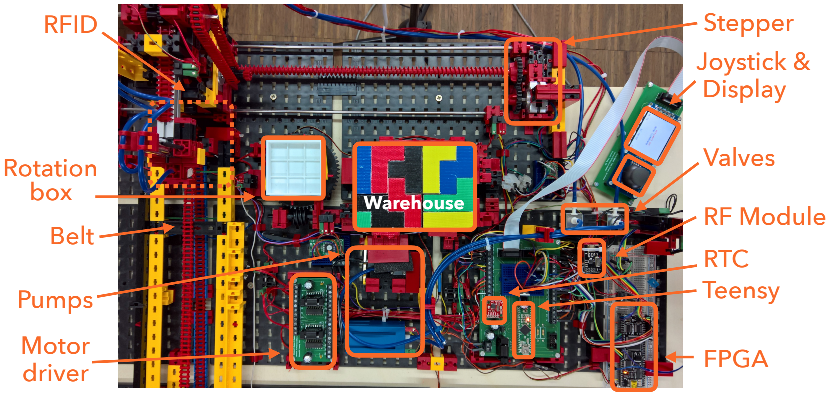

Fig. 3. Overview of S1 showing all relevant HW components and the mechanical setup.

sides. To pick up tetrominos, vacuum pumps and compressors connected to valves are used. The compressor lowers the robot arm while the pump produces vacuum to lift tetrominos. Valves are used to minimize the amount of residue pressure or vacuum in the pneumatic system, so that the procedure of picking up and laying down can be performed reasonably faster.

The brain of each station is a *Teensy++ 2.0* microcontroller featuring an *Atmel AT90USB1286 8-bit* core [3]. Besides a comparably large amount of program memory and SRAM, this controller also features enough pins to control the large amount of peripheral components. Furthermore, it can be programmed with the *Arduino* IDE [4] that has a large community and is said to be easy to use. Each station also possesses a *Xilinx Spartan-3A Field Programmable Gate Array* (FPGA) to protect the setup from erroneous code running on the microcontroller [5]. All stepper motors and the rotation box are connected to a protection circuit on the FPGA so that the SMF can not be damaged by uploading incorrect software onto the controllers. Further details about these circuits can be found in Section 5.1.

In order to enable a communication between the three stations (S1, S2, S3) and to use central and decentral information for making decisions, radio frequency modules (based on [6]) are used which operate at the 2.4 GHz ISM band. These modules offer both, unicast and broadcast message transmission to be able to send messages either to a specific station or to all stations at the same time. *Radio-Frequency Identification* (RFID) is used to mimic a "smart product" that tells the machine what to do. Therefore, a RFID with re-writable internal storage is mounted to each palette which is read or written by RFID readers installed at each station.

5 SMF Remote Access

Beside the hardware needed for the SMF's "production mode" additional components to enable remote access are added. Figure 4 gives an overview on how the remote access is realized and highlights special components introduced in the following.

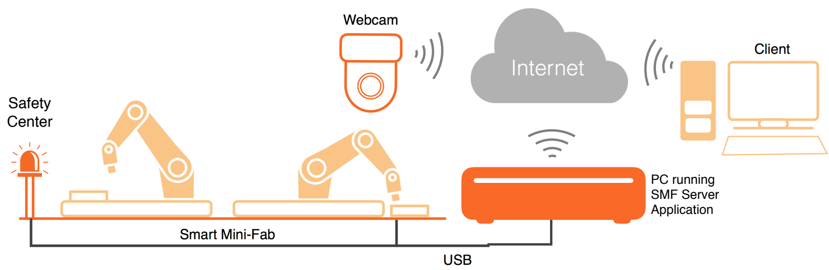

Fig. 4. Overview of the data flow needed for remote access. Additional modules are highlighted in dark orange.

5.1 Hardware

Since all components of one station of the SMF are controlled by a microcontroller, the entire functionality of the SMF is determined through the firmware running on the microcontrollers. To flash them USB connections to a development computer are established. This computer runs specialized software to enable the remote interconnection and the programming as discussed in Section 5.2 and is called "server" in the following.

As the aim of the work with the demonstrator is to perform a practical (production) task, optical feedback is essential. Especially, if the user is accessing the SMF remotely he or she needs to know whether the uploaded code leads to a correct operation of a station or not. Therefore, a webcam is installed directly above the Smart MiniFab.

A potential issue could arise if written code does not perform as expected or was uploaded incompletely. Since the user can not shutdown the hardware directly, unsafe conditions – e.g. if a robot arm continues to move towards its end-stop – can lead to damages. To prevent these situations, a *Safety Center* is connected to each station. This module is not directly accessible by the users. It consists of the already introduced Xilinx FPGA to which all end-stops and control signals are connected. The FPGA monitors these signals, detects potential dangerous situations and automatically performs emergency stops which disable all signals coming from the microcontroller. To provide programmers the possibility to properly react to end-stop presses a 100 ms delay is included in each safety center before an error is indicated; the signal, however, is blocked immediately. The safety center is directly connected to the server which is not only notified about the occurrence of a stop but also about its reason. Besides the self-stopping mechanism, users can also trigger emergency stops by themselves if they detect any failure via the webcam stream. Such an emergency request is forwarded to all safety centers which immediately block all outgoing signals.

Beside their safety functionality the safety centers also offer another teaching feature for students: One task could be to prove by formal verification methods that a bad state (a situation in which the SMF might be damaged) can not be reached, regardless of what has been uploaded into the stations' microcontrollers.

5.2 Software

The key element of the remote programming access for the SMF is the realized web application: It provides the possibility to input, develop, compile, and upload code to the SMF and, additionally, gives live feedback during the execution of this code. It is hosted on the server and is comprised of an individually developed server application and the client web application itself. The web application is executed on the user's computer as an interactive webpage based on HTML, *JavaScript*, and CSS. Figure 5 shows this webpage which can be easily accessed using standard web-browsers. The left side contains the programming section while on the right-hand side live feedback is given. The main part of the programming section is the code editor. Users can either upload their pre-written code or write a complete code from scratch in a C++ like language according to the Arduino [4] platform. All corresponding Arduino functions are available and proper code-highlighting and -indention is provided. Through a tab-based structure it is possible to maintain different code-files and to create classes with header-files. To store intermediate or final results, the code can be downloaded as a *ZIP*-file at any time. Furthermore, users can also compile and upload the written code. In this case, all files are sent to the server backend, compiled, and checked for compile-errors. The resulting hex-code is uploaded to the microcontroller which corresponds to the station the user has selected via a drop-down menu. The output of the compile and upload step is than sent back to the client and shown in the output field.

Live feedback is provided by a moveable and zoomable webcam at the upper right-hand side and an error output at the bottom on the right. If one or multiple safety centers, as introduced in the previous section, perform an emergency stop, the corresponding reasons are displayed. Emergency stops can also be triggered manually by pressing the stop button. The test-order field allows users to directly order pre-defined patterns of tetrominos for a quick test of their implementation. The order is received from the server and immediately forwarded to S3 of the SMF. A second way to place orders is provided through a button leading to a web-shop. This allows to configure and order arbitrary tetromino patterns.

To protect the web application from any unauthorized access a common user/password management is integrated. The access is currently limited to a single user at a time to avoid that two users programm the same station simultaneously, which may cause conflicts and confusion. In case of inactivity the user is automatically logged out after 20 minutes to prevent an accident or intentional blocking of the SMF.

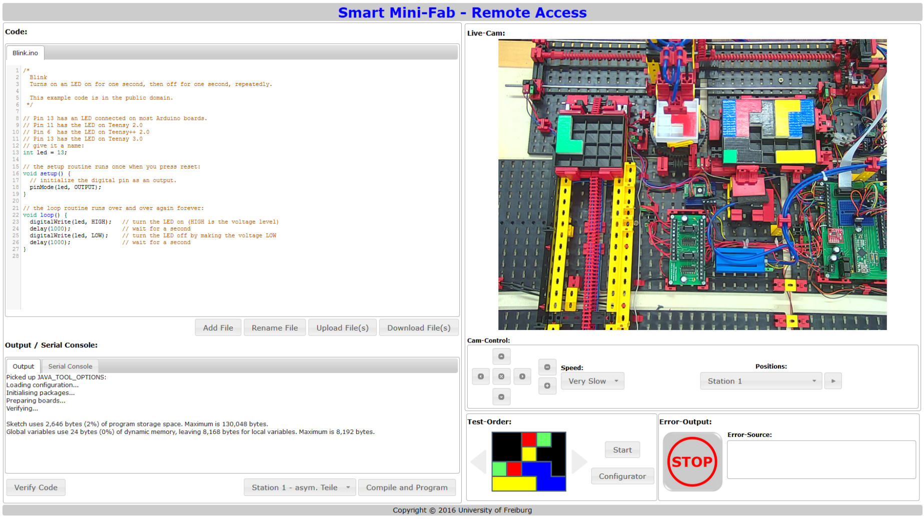

Fig. 5. Screenshot of the web application for the remote access to the SMF.

6 Lab Course

To give more students the opportunity to work with the SMF as the underlying HW environment, we are planning a new practical course in which students have to deal with IIoT related components like microcontrollers, RFID devices, and stepper motors and for which they have to provide software to control them. The lab course is divided into three parts:

1. **Software and Programming Introduction:** In the first part, the students get in touch with the web application and its visual feedback. To get familiar with the programming language lectures are given and the students will learn how to read and write analog values or digital states of I/O pins, how to use timers, how to call functions and how to develop classes.

To strengthen the newly acquired knowledge, the participants have to solve practical exercises by using the web application.

2. **SMF and IIoT concepts:** In the second part, the hardware modules of the SMF are treated in more detail, namely the stepper motors with their end-stops, the RFID devices, and the RF modules. This is achieved by practical exercises once again which have to be solved using the web application. In each exercise, a specific hardware module like a stepper motor with its end-stop is treated and the students have to develop code or, at best, a complete software module to control the hardware. Furthermore, the IIoT context of the used hardware is highlighted in more detail with the help of lectures.
3. **Project phase:** The last and major part of the lab course combines the knowledge of all previous exercises into one large project. The goal of the project is to solve a complex SMF task by dividing it into multiple subtasks that are executed by specific hardware components in a dynamic manner. In this part no strict exercise is provided as before, instead only the final goal is given to the students, meaning that the participants have to come up with a solution completely self-organized! Nevertheless, the organizers will support the students through the whole project phase by giving advice and feedback.

7 Related Work

The concept of a remote laboratory, shared hardware for interactive practical courses, and/or remote access for students has been of major interest since the upcoming of the internet. Different concepts exist in this area, depending on the hardware and the use-case under consideration. The general idea of a remote laboratory is compared to a competing hands-on laboratory in [7]. The authors performed a case study resulting in a comparable or even better performance of remote courses in contrast to corresponding on-site courses. A concrete example for a remote laboratory for hardware experiments with FPGAs, pattern generators, and measurement equipment such as logic analyzers is proposed in [8]. The presented system allows students to perform experiments with a FPGA attached to a PC from inside or outside the campus network. However, safety related regulation or protection is not mentioned at all and no visual feedback via webcam is provided. Video feedback has been added in a system developed at the University of Illinois [9] that allows users to access multiple servers with FPGAs attached. These can be programmed remotely while feedback is given by observing rudimentary LCD displays or LEDs attached to the FPGA with a webcam. However, the authors again do not provide information whether the hardware is protected. The solution proposed in this paper is, to our knowledge, the first that enables the remote access to IIoT related hardware. In contrast to the presented systems, it is possible to test complex software distributed to multiple subsystems from a single web application in which video feedback is given to observe moving parts of the SMF. On top of that, a protection circuit is added so that the system can not be damaged by uploading erroneous code.

8 Conclusion

This paper proposes a modular and expandable IIoT demonstrator called Smart MiniFab. It can be accessed from anywhere at any time via a web application which allows to remotely upload code to each of the microcontrollers placed in the SMF. Furthermore, the application provides visual feedback by a controllable webcam. Since code which is uploaded might be erroneous, a safety center was added to each station which checks for hazardous situations related to moving parts. If such a situation is recognized, the corresponding moving part is stopped and the user is informed.

As already mentioned, the SMF is divided into three stations. Another station is currently under construction and will feature a high-bay warehouse in which multiple palettes can be placed. Therewith, the demonstrator could be used to simulate even more complex scheduling and optimization tasks. Furthermore, a future version of the web application will feature a collaborate mode, in which students can work seamlessly on the same firmware version which will be managed by some kind of version control system such as *GIT*.

The positive feedback and enthusiasm received by students who actually worked with the demonstrator either for their complementary work or during practical sessions indicates that a remote access to interesting hardware should be integrated into the daily schedule of any student. Therefore, we are planning to use the SMF as the underlying HW environment in a new lab course to give a large number of engineering students the chance to perform experiments in the area of IIoT.

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