Teaching Sensor Fusion and Kalman Filtering using a Smartphone

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(a) The app main view.

(b) Live graph of sensor data.

(c) Log and streaming view.

(d) Sensor information dialog.

Fig. 2. Views from the Sensor Fusion app.

the descriptions in the lab instructions, an orientation filter should then be constructed. In the process, the students are given ample opportunity to use their filtering skills on a real application.

In order for the lab to have the expected effect, it is important that the students spend their time doing sensor fusion rather than trying to understand a complex framework in which to perform the task. For this reason, it has been important to implement the lab framework in such a way that the students can work completely in MATLAB, an environment they are familiar with from other courses.

In MATLAB the students are asked to implement the different steps in the orientation filter. Doing this they get practical experience from implementing the nonlinear EKF and for this how to linearize measurement equations. The results can directly be compared to orientation estimates available in the phone.

A fundamental component for successful signal processing is to understand the available signals and the studied system. Therefore, the first thing the students are asked to do is to get acquainted to the sensors and how they behave, and then to design simple calibration experiments. The students analyze the results and identify biases, potential drifts, and other peculiarities of the sensors. Different devices suffer from different problems, which makes the exercise extra interesting. Given their findings, the students should compensate their measurements. In practice this boils down to compensating for gyroscope bias. The calibration experiment is also used to get a good initial tuning for the filter.

The need for outlier rejection is easily illustrated by asking the students to shake their smartphone and/or to introduce magnetic disturbances. Not only does the students' textbook estimate fail, it is also easy to observe that the orientation estimate provided by the internal software in the smartphone automatically compensates for these effects. The students then implement their own outlier rejection and can then aim to outperform the built-in algorithm. Properly done, surprisingly good results can be achieved in short time.

Most important is the experiences the students gain in dealing with practical signal processing, realizing the difference between the theory and practice. Hopefully, the lab makes the students much more aware of the differences between textbook examples taught in the lectures and practical problems.

5. SENSOR FUSION APP

The Sensor Fusion app used in the described lab has been developed at Linköping University as an Android based teaching and demonstration platform for sensor fusion. The app is available for free under the name *Sensor Fusion app* [1] from Google Play Store for everyone with a device running Android v. 2.3.3 (Gingerbread) or later. This section describes the app; what it can do and how it can be used to create a real-time connection between the smartphone and, *e.g.*, MATLAB running on standard desktop computer. Currently, students without an Android device and those who do not want to use their own smartphone, are provided relatively cheap Google Nexus 4 smartphones [2] to use during the lab. The sensors in the Nexus 4 are evaluated in (Ma et al., 2013).

5.1 App Description

When starting up the Sensor Fusion app, the main menu appears as seen in Fig. 2(a). The menu offers the user the main functionality available:

- real-time visualization of sensor measurement, using *Select Sensor*;
- logging or streaming measurements, using *Log Data*; and
- getting information about what sensors are available in the current device, using *Sensor List*. (See Fig 2(d).)

[1] The Sensor Fusion app at Google Play Store: http://goo.gl/0qNyU

[2] Google Nexus 4 on Wikipedia: http://en.wikipedia.org/wiki/Nexus_4/
Google has at the time of writing this discontinued the Google Nexus 4 in favor of the Google Nexus 5 phone.

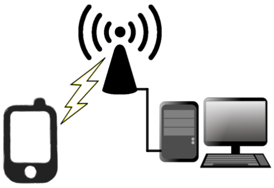

Fig. 3. The setup used to connect the smartphones to the computers in the lab during the lab session. The smartphone, to the left, is connected via WiFi to a wireless access point, that in its turn is connected to the computer, shown to the right, via a wired network.

The app also offers some options to configure its behavior.

The real-time visualization of sensor data works for all the main sensors available in modern Android device. Fig. 2(b) shows how gyroscope measurements are visualized. Each sensor view furthermore offers a dialog explaining what physical quantity the sensor measures, how it can be used, and suggests easy experiments to perform to gain a better understanding of the measurements. The ability to visualize measurements from the sensors direct on the smartphone is used in the initial stage of the lab to help the students get to know the sensors they use in the lab.

From the perspective of the lab, the streaming and logging capability of the app is the most important. From one unified view, see Fig. 2(c), it is possible to in real time stream selected sensors to a server and/or log the measurements to a log file on the device for off-line analysis. The streaming functionality is vital to the lab experience, and is therefore described in more detail below.

5.2 Streaming Measurements

The Sensor Fusion app streams data by opening a TCP connection to a minimal server program running on the receiving end, *e.g.*, MATLAB on a laptop or a lab computer. The app is fully configurable with regard to which IP address to stream data to and which port to use. The app can hence make use of any available WiFi and mobile Internet connection to stream the data. This also means it will automatically make use of VPN connections if present. This allows for easy use in almost any setting. It also makes it possible to use either a laptop or the device itself as a wireless hotspot to connect the two to obtain a truly mobile system not relying on any external infrastructure. In the labs, the students connect the phones to the local wireless network to stream the data. The lab setup is illustrated in Fig. 3 utilizing the normal WiFi infrastructure in the computer labs.

The computer receiving the streamed measurement data should run a small server. For this purpose, a small Java library is provided that can be downloaded via a link on Google Play Store. The Java library is written in such a way that it can be easily embedded in MATLAB or used stand alone as a part of a Java program that utilizes the streamed measurements. The format used to stream the data furthermore allows for quite easily developing servers in different languages if needed.

The MATLAB based server allows for full integration of the streamed measurements into MATLAB. At the beginning of the lab a skeleton of MATLAB code is provided, and the students then extends it during the lab. The code shows how to access the streamed data, and provides an easy way to visualize the orientations they estimate (see Fig. 4). The code skeleton is also available following the links on the app's Google Play Store page. By providing easy access to measurement data in this way allows students with limited coding experience to focus on the sensor fusion aspects of the lab, rather than on how to obtain data from the device.

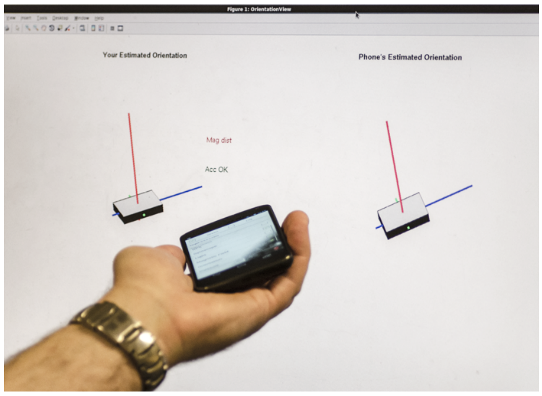

Fig. 4. Student evaluating his orientation estimate comparing the phone orientation with the estimated orientation on the screen on his own laptop.

6. DISCUSSION AND LESSONS LEARNED

At the time this paper is written, the lab and the Sensor Fusion app has been used in the Senor Fusion course once. The overall experiences are positive, but due to the limited experiences, it is too early to make any far-reaching conclusions. Hence, this section discusses ideas and experiences from the preparations, execution, and post-processing of the lab, and tries to relate this to available literature. Hopefully, this description can inspire others to construct useful labs for teaching sensor fusion.

In order to motivate the usage of a lab in a course, it should in a clear way help to fulfill the pedagogic goals of the course. In this case the pedagogic goals of the course is listed in Sec. 2. These goals will be referred to as *(i)* –*(ix)* below.

The described lab contributes to *(i)* (understanding fundamental principles of estimation theory) in that it allows and encourages the students to play around with a non-trivial estimation problem. During the lab the students experience how using (or not using) different signals affects the end result, as well as the effects of sensor bias, disturbances and outliers. Hence, the students are forced to think about how to use the signals available and if they should estimate biases or not. In order to do this they need to understand the underlying estimation principles.

The filtering problem requires a nonlinear filter (an EKF in this case) to be solved. This works toward *(v)* in the course. In the process, the students have to design and implement measurement models for three common sensors (accelerometer, gyroscope, and magnetometer). They furthermore experience problems, such as environmental disturbances and outliers, characteristic to these sensor types. This is part of the fulfillment of *(vii)*.

The lab is designed with the practical learning objectives for engineering labs, as formulated by Feisel and Rosa (2005), in mind. The students are part of the whole signal processing chain; collecting data from the smartphone, evaluating the data available and based on that, design the filter needed for estimating the orientation. Finally, they are then guided to put the solution in place. In the process learning from mistakes and experiences they make. The lab instructions are intentionally written in such a way that the students try simple things first, and are then forced to identify the shortcomings with these simple solutions and come up with solutions to them and re-engineer accordingly.

This practical hands-on approach to the lab is according to Ma and Nickerson (2006) a good way to prepare students for procedures common in the engineering profession. This relates closely to pedagogic goal *(ix)*. The main objection to hands-on labs is usually the economic cost to maintain expensive equipment. The lab presented in this paper is fortunately relatively cheap in material and maintenance. Many students use their own smartphones for data collection, and the smartphones offered to those without appropriate smartphone, or to those who do not want to use their own phones, can be acquired at a very affordable price compared to other lab equipment.

During the lab sessions, some students indicated they had played around with the app and the measurements before coming to the lab. This is a good sign that the topic of lab and the easy access to the free supporting software inspired these students to deepen their knowledge. Furthermore, the lab has proved to be compatible with a wide selection of smartphones making it very accessible. This is further demonstrated by almost two thirds of the students using their own smartphone during the labs and the close to 1 500 installations of the Sensor Fusion app.

It was also the experience during the lab that many students found the exercise engaging. They seemed positive to have a lab based around a smartphone, and enjoyed to see what they could do with the sensors many of them owned and carried around in their pocket each day. Hopefully, and as indicated by some of the students, they do not stop their laboratory work at the end of the time assigned for the lab. Contrary, hopefully the easy accessible smartphone to smartphone measurements invites to further experiments as suggested by Hofstein and Lunetta (2004). At the same time, the data collected in real-time allows them to experiment and analyze different solutions as they go on. This way the lab well complies with the four main principles for successful lab according to Kirschner and Meester (1988).

At the same time as using a smartphone for the lab seemed to engage most of the students, it also posed an initial barrier for students not acquainted to the technology. This is unfortunate, and shows how important clear instructions are and not to rely on students being familiar with the technology.

7. CONCLUSIONS AND FURTHER DEVELOPMENT

This paper describes a lab designed for the Sensor Fusion course at Linköping University. In the lab, the students estimate the orientation of a smartphone using measurements from the phone streamed in real-time from an app developed for the purpose. The app and the material for the lab are available for free. The initial experiences from the lab are positive and the students seem engaged.

The Sensor Fusion app can also serve as a demonstration platform for sensor fusion. The app can also be used to collect data for other purposes.

In the future, there are plans to extend the app so that it can collect an even wider range of data from the phone; such as signal strength from WiFi access points and other wireless cellular systems, as well as sound from the microphones and images from the built-in camera. This would allow for even more advanced usage of the app both in teaching and as a cheap sensor platform for conducting research.

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