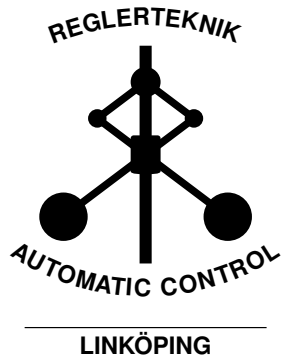


Sensor Fusion, TSRT14

Localization Using a Microphone Network

This version: 2023-04-20



Name: _____

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1 Introduction

This laboration is about localization using a network of sensors, a problem that is common in the sensor fusion world. A real world example of audio based localization is shooter localization. The sound of a gun being fired is quite distinctive and can be correlated with the recordings. Time of arrival at different microphones can be found, and the shooter can hence be located. Another example is localization of airplanes using radars.

You will use a network of microphones to localize a target that is emitting short sound pulses. To simplify things, the profile of the pulse that is being emitted is known. Hence, correlation can be performed with the recordings to find the *time of arrival* (TOA) of each pulse at each sensor. If the time of pulse emission is known, one can easily find the distance to the target using the (also assumed known) speed of sound. This gives a radial distance to the target, but not a bearing, and thus the target location could be anywhere on a circle (assuming a 2D world). Combining such circles for all the sensors, the intersection, which is where the target is located, can be found.

As in most real world cases, in this laboration, the time of emission is unknown. When all sensors are synchronized, one method of performing localization when time of emission is unknown, is to use *time difference of arrival* (TDOA). Knowing the TDOA, one can use the speed of sound to find the relative difference in distance between sensors and the target. Given all relative distances in the network, the location of the sound source can be found. For further information on TOA and TDOA, see Chapter 4 in [1].

2 Purpose of Laboration

During the laboration an RC-car will autonomously follow a planar, closed loop track, while simultaneously repeatedly playing a sound pulse, see front cover. The purpose of the laboration is to track the sound-emitting car by recording audio with four microphones, which will be used to provide TDOA measurements.

3 Equipment

The equipment used is briefly explained below.

Sound Card

The sound card is a *Behringer UMC1820*, see Figure 1, which allows up to 18 channel recording and 20 channel playback simultaneously. The sound card has a software interface called *UMC Control Panel* which enables the user to configure some settings such as sample rate etc. For more information about the sound card, see <https://bit.ly/2uxamRp>.



Figure 1: *Behringer UMC1820* sound card.

Microphones

There are four *Shure PG58* and four *Shure PGA58* microphones used for recording, for a total of eight microphones. The two sets of microphones are easily distinguishable, see Figure 2, and have similar performance. Since you will only be using four microphones to localize the car, two datasets may be collected simultaneously. For each dataset it is recommended to use the same microphones, i.e., use PG58 for one dataset and PGA58 for the other. Each microphone also comes with a microphone stand that is to be used during the lab, see Figure 2.

Target

The target in this laboration is an RC-car generously provided by the division of vehicular systems, see Figure 3. Using the Qualisys positioning system and an on-board IMU, the car can autonomously follow a pre-defined trajectory. To do so, it uses motion planning and control algorithms that are taught in the course TSFS12 - Autonomous Vehicles - planning, control and learning systems. On top of the car, a speaker is mounted that emits a known sound pulse approximately twice every second.

Environment

The laboration takes place in Visionen, which is equipped with a Qualisys positioning system. The system consists of a set of cameras that capture IR



Figure 2: *Shure PG58* and *Shure PGA58* microphones.

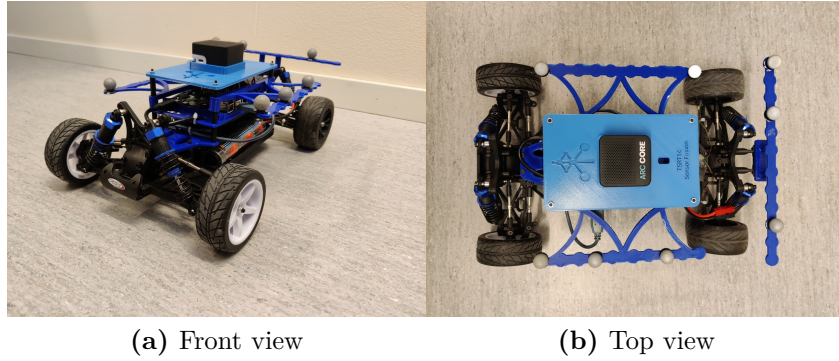


Figure 3: The autonomous RC-car.

reflections of a set of highly reflective markers that are placed on the Target, see Figure 3. The position of each marker can then be determined with more or less mm precision. By using several markers in a particular configuration, the position, orientation and velocity for the center of the Target can be recovered.

The positioning system serves two purposes, 1) it acts as an external positioning system for the RC-car, such that it can follow its pre-defined trajectory and 2) it acts as ground-truth for the laboration.

The recording environment (software) is based on the Robot-Operating-System (ROS). The software communicates with the RC-car through a graphical interface, see Figure 4. The software displays the desired trajectory of the car as well as the trajectory it actually follows in real-time. It has four functions:

1. **Start** - Runs the car along the pre-defined trajectory

2. **Reset** - Returns the car to the initial position.
3. **Stop** - Stops the car in place.
4. **Record** - Starts recording both audio and positional data and starts emitting the pulse via the speaker. Pressing a second time stops the recording and saves the data.

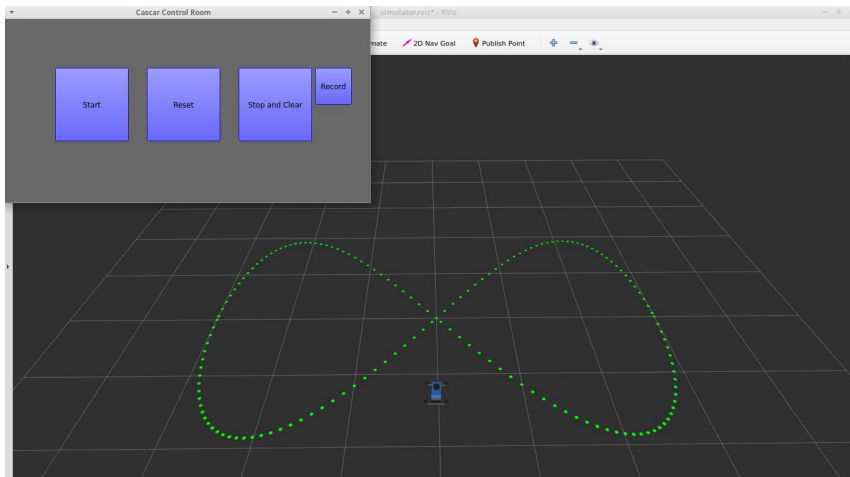


Figure 4: Recording software

TDOA quality estimation

The pulse detection in each microphone will vary slightly. This is modeled as a noise process acting on each microphone. To estimate the bias and variance of this noise, a calibration dataset should be collected by placing the microphones at the same distance from the speaker (the pulse should then enter the microphones at the same time).

Ground truth

During the lab, you will have access to “ground truth” via the Qualisys positioning system. Note that the data from Qualisys is *not* matched in time with the pulses that are emitted and detected via the microphones. Hence, the ground truth can be used to compare to visually/qualitatively, rather than quantitatively. However, should you want to compare to the ground truth quantitatively, you will need to match the Qualisys trajectory to the pulse data yourself.

4 Signal Processing

The robot emits a pulse train, where each pulse is a bi-directional *chirp* - a signal that sweeps from one frequency to another and then back again. The particular signal used here sweeps from 600 to 1400 Hz and back again. This signal is very distinct and thus quite easy to detect. The signal is shown in Figure 5.

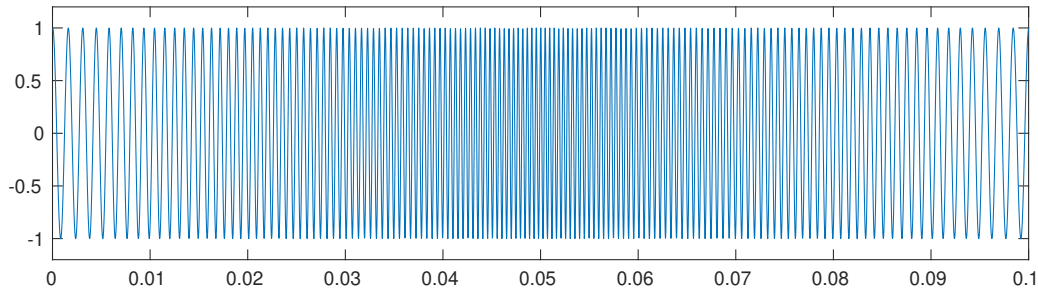


Figure 5: Chirp signal.

Since the emitted signal is known, it is possible to correlate the measured signals of the microphones with a copy of the pulse. This gives the cross-correlation and it will have quite distinct maxima. The maxima which will be the TOA on every channel. There will also be other maxima due to noise, echos etc. but these are hopefully less distinctive than the interesting peak. Since the robot is emitting a sequence of pulses, several maxima will be found. Even in situations with low *signal to noise ratio* (SNR), this method performs quite well.

In the laboration the car will play a signal with pulse width $t = 0.1$ s. The time between pulses is approximately 0.5 s.

5 Provided Code

The following MATLAB functions are provided:

- **SFlabRun** — the main script for pre-processing the recorded data.
- **SFlabFindPulseTimes** — finds the times at which pulses were detected in each input channel. These times can be used for TDOA localisation.

Type **help** followed by the function name in the MATLAB command prompt to see how to use the functions. A number of auxiliary functions are also provided, however, they are only used by the functions above and need not be called by the user. The MATLAB functions can be downloaded from the course homepage (<http://bit.ly/2uQfRL9>).

6 Preparations

- Read these lab instructions and make sure you have an overview of all the work needed to complete the lab, not only what is expected at the data collection session.
- Read Chapter 4 in [1].
- Plan at least two different microphone configurations. The two different configurations should correspond to fundamentally different situations.
- Download `SFlab1.zip` from the course homepage and unzip the files.

7 Tasks

The laboration is performed in groups of two students. Data acquisition is done in the lab, where all the necessary equipment is located. One 60 min time slot has been allocated for a set of four groups, which can be booked via the lab registration system. The remainder of the laboration is performed elsewhere using the collected data.

Note: The data collection session is just a small part of this laboration. You are expected to spend time with the tasks continuously throughout the course as you learn new techniques. Furthermore, this is an exploratory laboration; that is, part of the objective is that you yourself figure out exactly how to solve the posed problems. Hence, make sure to allocate time for the laboration work, and do not assume it can be finished the day before the deadline.

7.1 Data Collection

The first part of the lab is data collection. Perform the following tasks:

1. Use the suggested setup in Section 3 to obtain data to estimate the measurement precision.
2. Let the car follow the trajectory, while playing the sound. Record data with at least two different microphone configurations. Do not forget to note the microphone positions – these are available in the Qualisys positioning system! (Photos of the configuration are usually also helpful later on.) The two different configurations should correspond to fundamentally different situations. Plan your configurations before the lab session. Since there are *eight* microphones and you will only be

using *four* for localization, you will collect two datasets simultaneously. Record approximately 60 s of data for each configuration (this corresponds to the car driving the trajectory approximately twice). The audio data is automatically saved to a .wav file and the recorded positions from Qualisys is saved to a corresponding .mat file.

After recording the data, use the provided pre-processing script to verify that the data looks good. The .wav file contains the audio for all 8 channels which means that you will need to split the audio data into the two datasets manually.

7.2 Localization

When data has been recorded, the remainder of the lab should be performed elsewhere. The following tasks should be solved:

1. **Sensor calibration:** Describe the accuracy of the measurement (the estimated time of arrival) for each sensor in terms of the bias and standard deviation of its measurement noise. Use the matrix `tphat` from the calibration data to compute a vector of measurement errors `e` for each sensor (notice that this can be accomplished in different ways since the true time of arrival is unknown). Then compute histograms of the measurement errors and compare them to a normal distribution, using e.g. `histfit`. These histograms can be seen as empirical probability density functions of the measurement noise in each sensor. Also, compute the bias and the standard deviation of the measurement noise.
2. **Signal modeling:** Describe the different sensor models you will use in your localization algorithms. The models should be given both as equations

$$y = h(x) + e, \quad e \sim \mathcal{N}(0, R)$$

and as an m-file.

3. **Experiments:** Write a brief description of the microphone configurations, and the obtained data. The sensor locations and the target's initial position can, together with the m-file and noise distribution `pe` above, be used to construct a `sensormod` object. The configurations can then be illustrated with `sensormod.plot`.
4. **Configuration analysis:** Compare your two configurations using at least one of your sensor models in at least one of the following aspects:

- (a) Compute the *nonlinear least squares* (NLS) loss function $V(x) = (y - h(x))^T R^{-1} (y - h(x))$ on a grid over plausible target coordinates for a certain measurement y .
- (b) Compute the *Cramér-Rao lower bound* (CRLB) as a function of target position and represent this as a map over plausible target coordinates where each grid point gives a bound on the root mean square error $\text{RMSE} \geq \sqrt{\text{tr}(I^{-1}(x))}$.

Use this map to motivate your preferred configuration.

5. **Localization:** Estimate the position of the target at each time instant. Compare at least two of the following localization algorithms:
 - (a) NLS using a 3D grid search over $x = [p^T, r_0]^T$, where p corresponds to the position and r_0 to the unknown pulse emission time.
 - (b) NLS using a gradient or Gauss-Newton search over $x = [p^T, r_0]^T$.
 - (c) *Separable least squares* (SLS) using a *weighted least squares* (WLS) estimate of r_0 and a 2D grid search over p .
 - (d) A TDOA approach, where the pairwise differences of detection times for the M sensors are used to eliminate r_0 . Select one sensor as reference, construct the $M - 1$ pairwise differences, and use as measurements.
6. **Tracking:** First, select two motion models. Then, compare the following filters for both models (that is, you will get four estimated trajectories):
 - (a) Take the localization estimates above as the artificial measurements $y_k = \hat{p}_k + e_k$, $e_k \sim \mathcal{N}(0, P_k)$ at time instant k . Apply a *Kalman filter* (KF) (or *extended Kalman filter* (EKF) if your motion model is nonlinear), to the two different motion models in turn.
 - (b) Select one sensor as a reference. Make sure that this one gives good measurements. Use a TDOA measurement model with three TOA differences. Apply a *point mass filter* (PMF), EKF, *unscented Kalman filter* (UKF), or *particle filter* (PF), to the two different motion models in turn.
7. **Sensitivity analysis:** Select one of the methods above and empirically evaluate how sensitive the result is with respect to the specified

microphone locations (i.e. disturb the positions of the microphones). After all, these locations are measured by Qualisys, and contain an uncertainty. What is the size of this uncertainty approximately, and will it affect the result?

8 Lab Report and Submission Instructions

The laboration is not examined at site, but using a written report. The report should be written according to the following guidelines

- Hard limit on 6 pages
- Use the provided LaTeX-template (`.sty` and `.tex`), which you can find on the course homepage
- Report should be able to stand on its own, i.e., it should be understandable **without** this lab memo. Further, a person that did not just perform the lab should be able to follow your presentation.
- Report should include
 - A description of how the data was gathered. This includes the microphone positions, and a motivation why the particular positions were chosen.
 - Descriptions of how you solved the tasks in Section 7.2. Include plots that illustrate your results.
 - Well supported conclusions.
 - Code in an appendix. **NB: The code is not included in the page limit.**

Lastly, keep in mind that your report will be evaluated using the criteria listed in Section 9.

8.1 Grading procedure

The submission, review and grading of the lab report consists of five stages:

First submission of the lab report. The first submission of the lab report will be used for peer review. Please write your group ID on this lab report. Do NOT write your names or personal identity numbers on the lab report. This report will not be graded by the assistant. The first submission will also be sent to **Urkund** automatically as you submit it.

Submission of the peer review. The length of the review report shall be 1–2 pages. Do NOT write any names on the peer review. Start the report by quoting your group ID as well as the group ID of the lab report you reviewed. For instructions on how to perform your peer review, please read Section 9.

Final submission of the lab report and of the review response. The lab report needs to be updated based on the peer review resulting in a final version of the report. A review rebuttal also needs to be written. In this review rebuttal, the comments of the reviewers need to be addressed and updates to the report need to be discussed. Please write your names and personal identity numbers on this version of the lab report!

Grading of the lab report, peer review and review rebuttal. The lab report, the peer review and the review rebuttal will be read by the assistant and given one of the following grades; pass, revisions needed, or fail.

Possibly submission of a revised version. If revisions are needed, a new version of the report must be handed in.

The deadlines for each of these stages can be found on the course webpage. If the updated version does not pass or the report is failed at first hand in, a new version will be read and graded in conjunction with the next course exam.

8.2 Submission

The submissions are handled through Lisam under “Submissions”. The procedure is as follows:

1. One group member submits the first draft and adds the other group members to that submission. Any students not in a submission group will not be able to get credits for the lab. Please name your group after the group ID provided by the course assistant in the beginning of the course.
2. Your submission will then be marked as “needs completion” and another group’s report will be provided to you. Review the report and resubmit your review in the same interface.

3. Your submission will again be marked as “needs completion” and you will receive the peer review of your report. Make the necessary adjustments and resubmit your report in the same interface.
4. Should you require adjustments after the assistants’ comments, the submission will yet again be marked as “needs completion”. If so, review and submit a final report. When you have submitted your final report, the assistant will review the report and assign a pass or fail grade.

9 Peer Review

In the peer review, your task is to provide feedback to help the other students to improve their report, and also to allow you to learn from seeing how other people write their report. Shortly after handing in your lab report you will receive another group’s lab report from the course assistant. Read this lab report and write a review report. Check the course homepage to find out when the review report is due. In the review report you should respond and discuss the following questions

1. Are the data sets presented clearly? Are the procedures to acquire data described in enough detail for the experiment to be repeated by someone else?
2. Is there a clear explanation of the solutions of the tasks in Section 7.2? Discuss each task 1–7 separately.
3. Are the conclusions well supported by the data, the experiment and the results? Do you agree with the conclusions? What would you like to add to the conclusions, based on the data and the results of the task?
4. What is a particular strength of this lab report? Discuss the content, not the format.
5. What suggestions can you provide to improve the overall quality of the report? Discuss clarity, readability and technical accuracy.

The questions shall be answered in the form of a discussion, present arguments for your point of view and propose alternative methods. Some more specific tips:

- Present useful criticism and make sure your comments are constructive.
- Use a positive tone and consider how you would feel if someone sent your review to you.

- Be clear and specific about things you think could be improved.
- Point out strengths as well as weaknesses.
- Use a courteous language.
- Avoid comments that might be read as insulting or inappropriately personal.

Most people ignore feedback that they find hostile, vague, or confusing. Try to keep your comments positive and specific: this will make them much more useful to your peers.

NB: The review that you write will also be evaluated by the lab assistants. It is a part of the examination of this lab.

References

- [1] Fredrik Gustafsson. *Statistical Sensor Fusion*. Studentlitteratur, Lund, Sweden, 3. edition, 2018.