Multi Sensor Ramp Detection and Localization for Autonomous Valet Parking

Master thesis

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Add Expleo stuff + MDT Logo

Kurzfassung

100-200 Wörter Kurzfassung (deutsch)

Abstract

100-200 word abstract (english)

Declaration

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und eigenhändig sowie ohne unerlaubte fremde Hilfe und ausschlielich unter Verwendung der aufgeführten Quellen und Hilfsmittel angefertigt habe.

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Glossary

AHRS Attitude Heading Reference System. 11

FIR Finite Impulse Response. 10

FOV Field Of View. 9

GPS Global Positioning System. 3

IIR Infinite Impulse Response. 10

IMU Intertial Measurement Unit. 5

LiDAR Light Detection And Ranging. 8

MEMS Microelectromechanical Systems. 5

RADAR Radio Detection And Ranging. 8

SONAR Sound Navigation And Ranging. 8

Todo list

Chapter 1

Introduction

1.1 Motivation

Parking is one of the most challenging driving tasks and the cause of almost half of the car accidents [14]. Current cars are already able to fully automated park on their own in parallel or perpendicular parking spaces. But due to the very limited space in cites, parking garages are often used in central areas [1]. Automated valet parking (AVP) allows for a fully automated parking experience. The car is left in a drop-off zone and finds a parking spot on its own. Afterwards the driver can give a command and the car leaves the parking spot again and picks up the driver. AVP saves time, the hassle of remembering the parking level and spot and furthermore allows to use the available space more efficiently and also minimizes the risk of collisions. For this to work an exact mapping of the environment and localization of the car in the garage is necessary.
This can be done either by simultaneous localization and mapping (SLAM) or the area can be mapped beforehand (e.g. using lidar sensors) in which case only a localization of the car is necessary. The mapping can be done in 2D or 3D. 2D maps only show information of the current level. Hence if the car is driven up or down a ramp, the new map of the corresponding floor has to be loaded. Because the localization usually only works in a 2D-plane, a change of levels would not be detected. To solve this problem, a ramp detection has to be implemented.

Just copied this from the expose, needs improvement

maybe some more sections about the specific topics or about goals

1.2 Outline

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Chapter 2

State of the art

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2.1 IMU

In [3] different methods to estimate the road grade angle are discussed. There exist methods without Inertial Sensors relying on a model describing the longitudinal movement of the vehicle and the topology of the road. Both models are fused using a Kalman filter to improve the accuracy of the estimation [13]. A Kalman filter is also used in [12], where vehicle sensor data and Global Positioning System (GPS) data are fused. Besides the road grade, the vehicle mass is often also unknown and estimated as well [12, 5]. Another method using GPS data and IMUs to calculate the vertical and horizontal velocity change respectively and thereby the road grade is proposed in [11]. [20] omits the IMU and relies on a GPS sensor and a barometer. THe problem with most of these methods are the use of a GPS sensor, which is not precise and most importantly will not work in parking garages. Furthermore many internal measurements such as the engine torque, brake system usage, selected gear etc. can not easily be accessed and thus might not be available.

Not really IMU, maybe in prev section instead

source?

why

A method which does not use GPS, but only accelerometers and wheel odometers instead is described in [6]. The vehicle acceleration, calculated by deriving the wheel speed measurements in respect to time, is subtracted from the accelerometer signal in longitudinal direction. The remaining part is then the gravitational acceleration and can be used to calculate the road grade angle. A similar approach is used in [15].

Maybe first write about acceleration only method, describe its problems, and then the improve methods such as complementary filter (adds gyro)

Read

[2] apparently even better than complementary filter or acceleration method. More about [7] (is actually used for the implementation by me). ...

Now that foundation of available is briefly explained, write something more specific about the methods which will be used. Or does this go in another section?

2.2 LiDAR

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2.3 Camera (optional)

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Chapter 3

Background

3.1 Mathematical

Might not be neccessary

3.2 Sensors

3.2.1 IMU

An Intertial Measurement Unit (IMU) is used to track the orientation and position of an object. Common uses are in the aerospace or automotive industry, often in combination with other sensors, to give information about the pose and position of a vehicle. More recently with the invention of Microelectromechanical Systems (MEMS) and specifically MEMS-IMUs which allow for a very small form factor at a low cost, IMUs are also used in consumer electronics such as smartphones or fitness tracker. An IMU usually consists of the three following sensors. The acceleration is measured using an accelerometer and can be used to determine the velocity and the covered distance by integrating once respectively twice. The gyroscope gives information about the change of orientation. Often times a magnetometer is used as well, which is able to measure the earth's magnetic field and is used to correct the measurements of the gyroscope. It allows for the determination of the absolute heading, whereas the gyroscope can only measure relative change. But because it is very sensitive to other magnetic objects, it is often omitted. IMUs can be typically divided into the two following categories.
In the first type, the stable platform systems, the inertial sensors are mounted in such way, that they are always aligned with the reference frame. This is achieved using gimbals, which allow movement along all three axes. The gyroscopes on the platform measure the rotation and send them to torque motors, which rotate the gimbals to keep the platform in alignment with the reference frame. The advantage of stable platform systems is that the calculation of orientation and position is straight forward. The angles of the gimbals can be measured to get the orientation and to get the position, the accelerometer measurements have to be be corrected for gravity (which is $9.8\,\mathrm{m/s^2}$ in upward direction) and be integrated two times. No coordinate transformation is necessary. The disadvantages are that the mechanical structure of the setup is complex, needs regular maintenance, requires a lot of space

reference?

and has high costs.
The second type are strapdown systems, which are mostly used today. As the name suggests all the parts are fixed onto the device and are thus not anymore always aligned with the reference frame. Advantages are that due to the lack of gimbals and motors a significantly smaller build is possible and lower production costs can be achieved. A disadvantage is that the calculation of the orientation and position is more complex, the rate gyroscopes have to be integrated to get the orientation and can then be used to transform the accelerometer signals into the reference frame. But with the decrease of computational cost this disadvantages continues to diminish. And even though they are continually improved, the accuracy does not quite match the of stable platform systems.
There are many different types of gyroscopes and accelerometers such as mechanical, optical or solid state, but only the functionality of MEMS will be described, because those will also be used in the experiment. Information about the working principle of other systems and also much more information about IMUs in general can be found in [19].
MEMS consist of electrical and/or mechanical components in the size of 100 nm to 1 mm, allowing for a very small form factor. Other characteristics of MEMS are that they can easily be mass produced allowing for low cost and usually also need less power than traditional systems, because everything is integrated on the chip [16]. Almost all consumer grade electronics uses MEMS-IMUs nowadays, but they also find more and more use in many industry segments, as their accuracy continues to improve [8].

MEMS Accelerometer

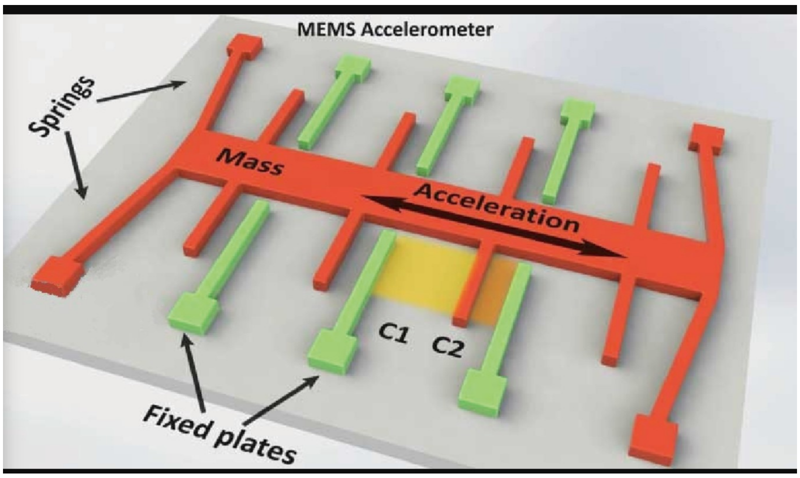

Figure 3.1: Micro structure of a MEMS accelerometer

The accelerometer is used to measure the acceleration. Besides dynamic acceleration there is the static and constant gravity acceleration on earth in upward direction. This allows for the determination of one axis of the IMU, even if it is not moving. Often times only the dynamic accelerations are of interest and to get them the acceleration data during stand still must be measured and subtracted. The micro structure of a MEMS accelerometer is shown in figure 3.1. A mass is suspended by springs along one axis and if an acceleration along this axis occurs, the mass moves in the opposite direction due to Newton's second law. The mass has little fingers perpendicular to the moving direction axis, which affect the capacity between the fixed plates. The change of capacity and thus voltage can be measured, from which the acceleration can be calculated. To be able to measure the acceleration along all three axis the same setup is used three times, perpendicular to each other.

MEMS Gyroscopes

A gyroscope measures the angular velocity. The setup of a MEMS gyroscope is similar to that of a MEMS accelerometer. A proof mass is suspended on a frame and responds to an input force. MEMS gyroscopes make use of the Coriolis effect, which states that an rotating object with the angular velocity w of mass m and velocity v experiences a force

$$F_C = -2m(w \times v).$$

To measure the effect, a mass is vibrating along one axis, which in turn is also suspended. If the mass is oscillating along one axis and a rotation is applied, a second oscillation on the axis perpendicular to the rotation axis can be observed. E.g. if the mass oscillates along the x-axis and a rotation around the z-axis is applied, a vibration along the y-axis can be observed. By measuring the amplitude and phase of the secondary oscillation the absolute value and direction of the angular velocity can be calculated. While MEMS gyroscopes do not achieve the same accuracy as optical gyroscopes they offer many advantages such as smaller physical properties (weight and size), lower power consumption and startup time as well as a significantly lower cost. Optical gyroscopes cost in the range of $10,000 whereas MEMS gyroscopes can cost as low as $3 [8]. But this comes at the cost of a worse angle drift which increases from 0.01 to 0.1 deg/h for optical gyroscopes to 10 deg/h for MEMS-IMUs. MEMS gyroscopes have replaced other gyroscope types in most areas, but in areas where the highest precision possible is necessary, typically in military industry, optical gyroscopes are still used today.

SIUnit

check what type of deg/h there are, daytoday vs in-run

(MEMS) Magnetometer

Sth sth lorenz (short because not used)

The disadvantages are that the magnetometer is easily influenced by other ferromagnetic material and electronic devices. Therefore indoor use while getting reliable data is rarely possible.

Typical MEMS errors

Maybe a sentence about idc about problems, because raw measurements are mostly used. The first type of errors are calibration errors, which can be eliminated. Common calibration errors are a constant bias (offset), scaling or misalignment (axes are not orthogonal to each other). The turn-on bias is different each time the IMU starts up, but can be removed as well.

- Calibration errors
- Turn-On Bias
- Bias instability
- Bias Correction methods
- VERY BRIEF
- maybe as table

3.2.2 Lidar

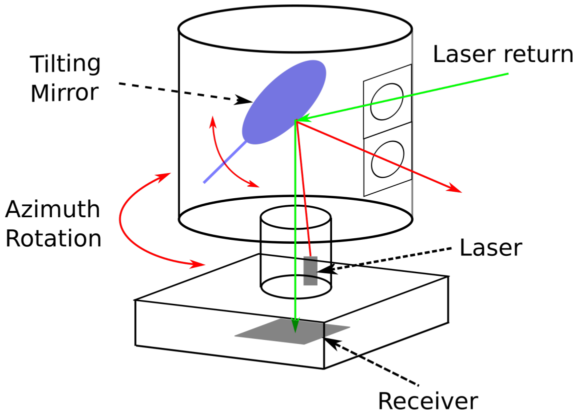

Figure 3.2: Setup of a mechanical spinning Lidar [4]

Light Detection And Ranging (LiDAR) is a method to measure distance to objects. Similar to other systems such as Sound Navigation And Ranging (SONAR) or Radio Detection And Ranging (RADAR), LiDAR uses the time-of-flight principle. A short laser pulse with the velocity v is sent into the environment and the reflected light is analyzed. The duration Δt it took from sending to receiving can then be used to calculate the distance s with

$$s = v\frac{\Delta t}{2}.$$

The change of intensity and wavelength of the returning light are measured as well and can provide information about the reflectivity of the object (intensity) or the chemical composition of the air (wavelength). Common uses of LiDAR are the analysis of earth's atmosphere, 3D mapping of environments or in the field of autonomous driving for object detection, tracking and simultaneous localization and mapping (SLAM). Basically all applications which use RADAR can also be used with a LiDAR instead, allowing for a greater accuracy.

There are different LiDAR types but the principles are similar. A transmitter generates a signal and sends it into the environment using a scanning system and a transmission optic. As transmitter a laser with a wavelength of 850–950 nm (near-infrared) is typically used. The scanning system allows the laser to explore a large area instead of only a single point by steering the light at different azimuths and vertical angles and can be divided in mechanical spinning or solid state systems.

Mechanical spinning systems is the oldest technology and is still mainly used today. A mirror which can be rotated around an axis is used, allowing for a greater vertical Field Of View (FOV). Also the whole LiDAR base on which the laser is mounted can be rotated independently from the mirror, allowing for a 360 horizontal FOV. To get a sufficient resolution the LiDAR has to spin at a high speed, but some LiDARs also use additionally a vertical array of lasers instead of only one to further increase the density of the generated point cloud. The working principle of a LiDAR using the mechanical spinning method is shown in figure 3.2. While mechanical spinning systems are very precise, they are bulky, need a lot of power and are expensive.

Solid state systems and especially MEMS LiDARs try to overcome those problems. MEMS LiDAR are quasi-static, the only part that moves is the on the chip embedded mirror, but due to the small size (1–7 mm diameter) very little power has to be used to move it. They can be rotated on up to two axes, but because the laser cannot be rotated a horizontal view of 360 is not possible . But advantages compared to mechanical systems are the smaller former factor and lower cost.

fact check, might have understood it wrong

After transmitting the laser signal the reflected light passes through the receiving optic and is received by photodetectors. A processing unit then generates a 3D point cloud from all the received measurements.

Sort citations and maybe add some more

[18] [17]

3.3 ROS

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3.4 Sensor Fusion stuff (maybe)

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3.5 Signal processing

. . . is necessary. . . . can be divided into filtering and smoothing. Filtering can be used in live applications and produces an estimate of the current value by taking the past values into account, whereas smoothing uses past and future samples and thus introduces a delay if used on live data . Because the detection should be live, only the filtering methods will be examined.

filtering also often introduces a delay

How much about dsp? E.g. also noise, aa etc or only type of filters?

Digital filters can be generally divided into two different categories. Finite Impulse Response (FIR) filter rely on a fixed number of recent input values. An example would be the moving average filter, which takes the past n values into account. Infinite Impulse Response (IIR) filter rely on previous output as well as most recent input by summing all points with a certain weight (e.g. exponential filter). This also explains the naming of the two types, the FIR filter "forgets" past values, whereas the IIR filter uses the previous estimate and thus theoretically takes all past values into account.
Savitzky-Golay filter

$$y = \frac{1}{h} \sum_{i=\frac{1-m}{2}}^{\frac{m-1}{2}} C \tag{3.1}$$

Chapter 4

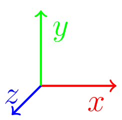
Experimental Setup

4.1 Sensors

4.1.1 IMU

Figure 4.1: myAHRS+ IMU this is the long caption which does not show up in list of figures

higher resolution + trim; add coordinate system



For the experiments the myAHRS+, a low cost high performance Attitude Heading Reference System (AHRS) will be used. An AHRS contains an IMU and outputs the raw data but also has an integrated Kalman filter which calculates the pose in form of quaternion or euler angles. It offers an micro-USB interface and runs with up to 100 Hz. It can capture a change of ±2000 dps (degrees per second), ±16 g and ±1200 µT. During the experiment only a fraction of this range is expected to be reached, hence the sensor seems suitable. Besides the hardware the unit already has an Extended Kalman Filter (EKF) on board. The EKF fuses the measurements of the three sensors and estimates a quaternion (and sth else?) from it. But this will not be used.

4.1.2 Lidar

Two different LiDARs will be used during the experiment. The RS-Bpearl and the Velodyne UltraPuck. The most relevant specifications of the two LiDARs can be seen in table 4.1. Both are mechanical LiDARs and have the same number of laser channels, but the Velodyne has a significant better vertical resolution, due to the smaller vertical FOV.

Table 4.1: Comparison of the two used LiDARs [10][9]

	RS-Bpearl	**Velodyne Ultra Puck**
Channels	32	32
Range	100 m	200 m
Range accuracy	±3 cm	±3 cm
Horizontal FOV	360°	360°
Vertical FOV	90°	40°
Horizontal resolution	0.2–0.4°	0.1–0.4°
Vertical resolution	2.81°	0.33°
Frame rate	10–20 Hz	5–20 Hz
Laser wavelength	905 nm	903 nm
Points per second	576,000	600,000

Missing figure

Picture of robosense or/and velodyne

4.1.3 Placement

The LiDAR will be placed on top of the car, to get a greater FOV. The pitch angle at which the LiDAR will be mounted should be chosen so that the number of points in the area at the beginning of the ramp are maximized. This allows for an easier detection of planes with different inclination angles. The coordinates at which the lasers hit the ground and ramp depend on the height of the LiDAR h_{L}, the distance to the ramp d, the angle of the ramp α, the pitch angle γ at which the LiDAR is mounted and finally on the vertical resolution and FOV of the LiDAR. The coordinates can be calculated in the following way.
Up to d the points will hit the ground, the

Make a good sketch again with labels etc and check if its easy understandable, only then continue in tikz and latex

$$\alpha \tag{4.1}$$

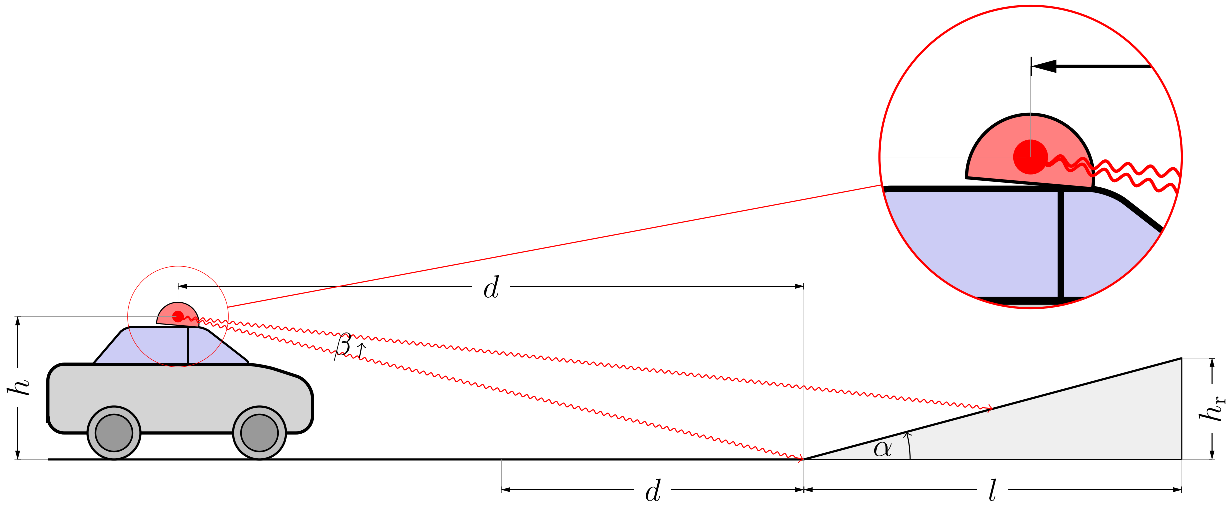


Figure 4.2: Mounting of the LiDAR

$$c = h - \frac{z}{\tan \alpha}$$

4.1.4 Odometry

- What is it and where used
- very short how does it work
- maybe calculation of velocity from ticks here

4.2 Car

Picture of eGolf

4.3 Garage

Missing figure

Picture of ramps or figure of ramps showing angles

Chapter 5

Methods

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5.1 IMU only

5.1.1 Calibration

Because the measurements of the IMU are measured in the coordinate frame of the IMU $\mathcal{I}$, which is not aligned with the car frame $\mathcal{C}$, they have to be transformed. This can be achieved using a rotation matrix ${}^{\mathcal{I}}_{\mathcal{C}}\mathbf{M}$ which transforms the measurements of the linear acceleration ${}^{\mathcal{I}}\mathbf{a}_n \in \mathbb{R}^{1\times 3}$ and angular velocity ${}^{\mathcal{I}}\mathbf{v}_n \in \mathbb{R}^{1\times 3}$ into the car frame. $n \in \mathbb{N}$ is the time step.

During standstill, the only measurable acceleration besides noise and bias is the acceleration due to gravity. Assuming the car stands on flat ground, the gravity acceleration in the car frame is measured in upwards z-direction. In a first step, the measured linear acceleration (gravity) in the IMU frame will be aligned with the z-axis of the car. According to Euler's rotation theorem, which says that any arbitrary rotation of a rigid body while holding one point (origin) fixed can be achieved by a rotation around a single fixed axis passing through the origin, there exists one rotation axis $\mathbf{j}$ and rotation angle α to achieve this.

In the first step, a quaternion ${}^{\mathcal{I}}_{\mathcal{B}}\mathbf{q}$ which transforms the measurements from the device frame $\mathcal{I}$ to an intermediate coordinate system $\mathcal{B}$, which has the z-axis up, will be found. Resulting in ${}^{\mathcal{B}}\mathbf{z} = {}^{\mathcal{C}}\mathbf{z} = \mathbf{e}_{\mathrm{z}} = \begin{pmatrix} 0 & 0 & 1 \end{pmatrix}^\top$. This usually is not the case for the other axes ${}^{\mathcal{B}}\mathbf{x} \neq {}^{\mathcal{C}}\mathbf{x}$ and ${}^{\mathcal{B}}\mathbf{z} \neq {}^{\mathcal{C}}\mathbf{z}$. Using linear algebra the rotation axis

better explaination

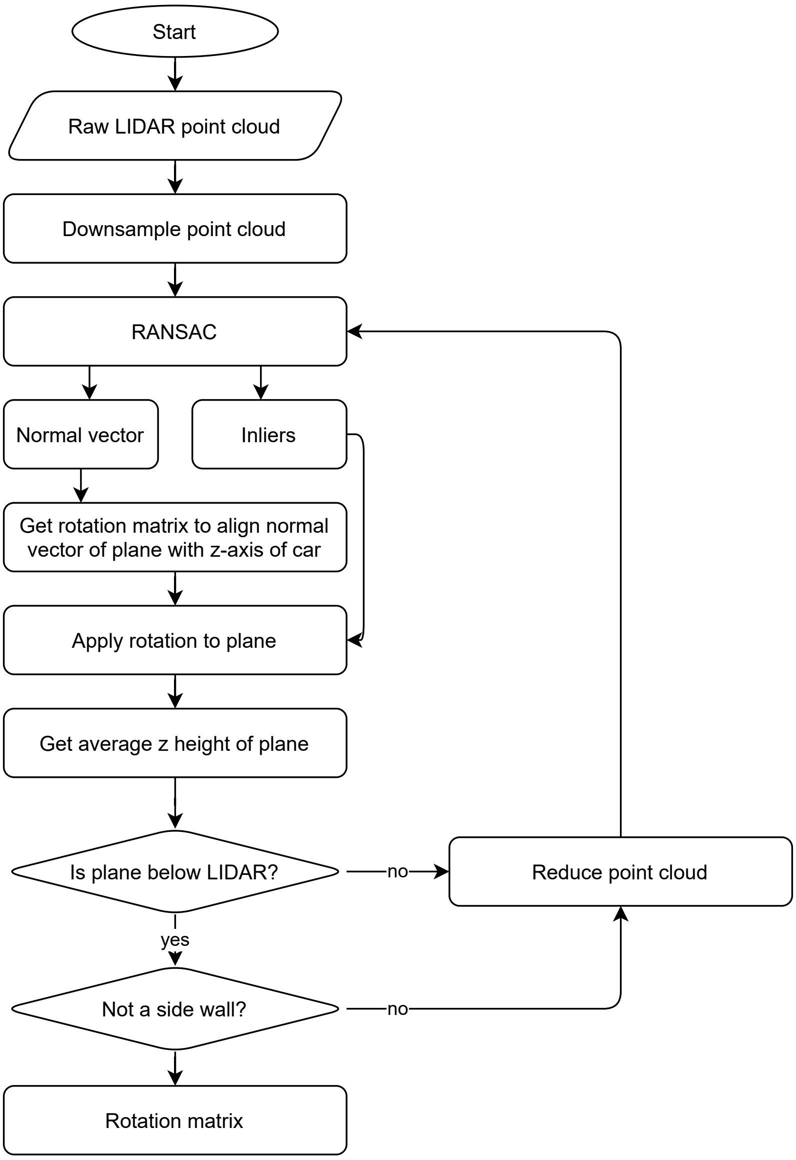

Figure 5.1: Algo for lidar alignment

$\mathbf{j}$, which is perpendicular to ..., can be found with

$$\mathbf{j} = \frac{{}^{\mathcal{I}}\hat{\mathbf{a}} \cdot {}^{\mathcal{C}}\mathbf{a}}{\|{}^{\mathcal{I}}\hat{\mathbf{a}} \times {}^{\mathcal{C}}\mathbf{a}\|} = \frac{{}^{\mathcal{I}}\hat{\mathbf{a}} \cdot \mathbf{e}_{\mathrm{z}}}{\|{}^{\mathcal{I}}\hat{\mathbf{a}} \times \mathbf{e}_{\mathrm{z}}\|} = \frac{{}^{\mathcal{I}}\hat{\mathbf{a}}_{\mathrm{z}}}{\|{}^{\mathcal{I}}\hat{\mathbf{a}}_{\mathrm{y}}\mathbf{e}_{\mathrm{x}} - {}^{\mathcal{I}}\hat{\mathbf{a}}_{\mathrm{x}}\mathbf{e}_{\mathrm{y}}\|} \tag{5.1}$$

with $\mathbf{a} \in \mathbb{R}^{1\times 3}$ being the measured linear acceleration (average) in the IMU or car frame respectively and $\hat{\mathbf{a}}$ being the unit vector of it.
The rotation angle can be calculated using

$$\tan(\alpha) = \frac{\left\|{}^{\mathcal{I}}\hat{\mathbf{a}} \times {}^{\mathcal{C}}\mathbf{a}\right\|}{{}^{\mathcal{I}}\hat{\mathbf{a}} \cdot {}^{\mathcal{C}}\mathbf{a}} \implies \alpha = \arctan\left(\frac{\left\|{}^{\mathcal{I}}\hat{\mathbf{a}} \times {}^{\mathcal{C}}\mathbf{a}\right\|}{{}^{\mathcal{I}}\hat{\mathbf{a}} \cdot {}^{\mathcal{C}}\mathbf{a}}\right) \tag{5.2}$$

resulting in the quaternion

$${}^{\mathcal{I}}_{\mathcal{B}}\mathbf{q} = \begin{bmatrix} \mathbf{j} \cdot \sin\left(\frac{\alpha}{2}\right) \\ \cos\left(\frac{\alpha}{2}\right) \end{bmatrix} \tag{5.3}$$

Decide for a notation (w,x,y,z is more common I think)

Now that the z-axes of both frames are aligned, the x- and y-axis can be aligned by a rotation around the z-axis. To find this rotation angle β, the car has to be accelerated forward. Then different rotation angles will be tested (brute-forced) until only the x-axis will measure an acceleration. The resulting quaternion ${}^{\mathcal{B}}_{\mathcal{C}}\mathbf{q}$ can then be concatenated with the previous quaternion to get the final quaternion

$$ {}^{\mathcal{I}}_{\mathcal{C}}\mathbf{q} = {}^{\mathcal{B}}_{\mathcal{C}}\mathbf{q} \otimes {}^{\mathcal{I}}_{\mathcal{B}}\mathbf{q} \tag{5.4} $$

A quaternion of the form $\mathbf{q} = \begin{bmatrix} w & x & y & z \end{bmatrix}^\top$ can be converted to a rotation matrix with

$$ \mathbf{M} = \begin{bmatrix} 1-2y^2-2z^2 & 2(xy-zw) & 2(xz+yw) \\ 2(xy+zw) & 1-2x^2-2z^2 & 2(yz-xw) \\ 2(xz-yw) & 2(yz+xw) & 1-2x^2-2y^2 \end{bmatrix} \tag{5.5} $$

And finally the measurements $\mathbf{A}$ can be transformed using

$$ {}^{\mathcal{C}}\mathbf{A} = {}^{\mathcal{I}}_{\mathcal{C}}\mathbf{M} \cdot {}^{\mathcal{I}}\mathbf{A} \tag{5.6} $$

$\mathbf{j} \in \mathbb{R}^{1\times 3}$, $\alpha \in \mathbb{R}$, $\mathbf{A} \in \mathbb{R}^{n\times 3}$ with n measurements, $\mathbf{M} \in \mathbb{R}^{3\times 3}$
Einspurenmodell: ... give the wheel speeds. To get the car velocity from the individual wheel speed measurements one can use a ... model.

$$ v_{\text{car}}(t) = \frac{v_{\text{rear,left}} + v_{\text{rear,right}}}{2} \cdot \cos(\gamma) \tag{5.7} $$

$$ \alpha(t) = \frac{v_{\text{rl}} - v_{\text{rr}}}{d} \tag{5.8} $$

$$ \gamma(t) = \frac{\alpha}{f_{\text{odom}}} \tag{5.9} $$

better explaination

with v_{rl} and v_{rr} being the wheel speeds of the rear right and rear left wheel respectively. γ is the yaw angle of the car, and α ?, d the wheelbase.
The car's acceleration

$$ a_{\text{car}}(t) = \frac{\mathrm{d}}{\mathrm{d}t} v_{\text{car}} \tag{5.10} $$

but because discrete numerical differentiation e.g. forward difference with step size h

$$ a_{\text{car}}(h) = \frac{v_{\text{car}}(x+h) - v_{\text{car}}(x)}{h} \tag{5.11} $$

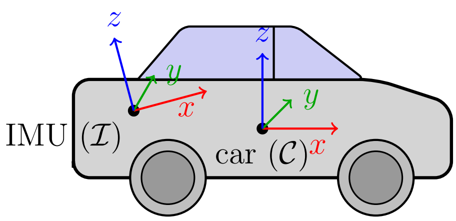

Figure 5.2: Coordinate frames (graphic might not be necessary)

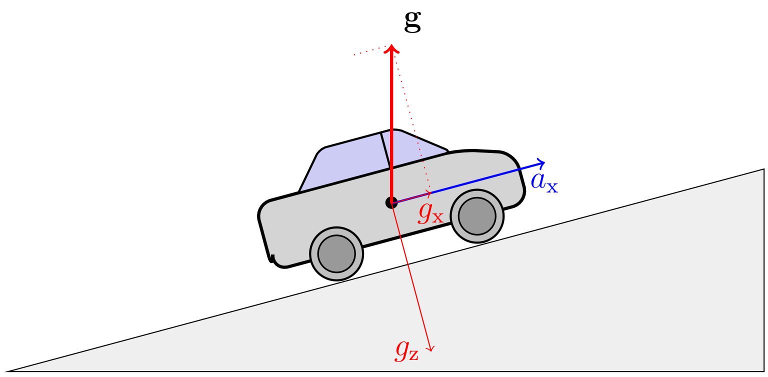

Figure 5.3: Gravity measured by IMU (in car frame). Show that g_z etc

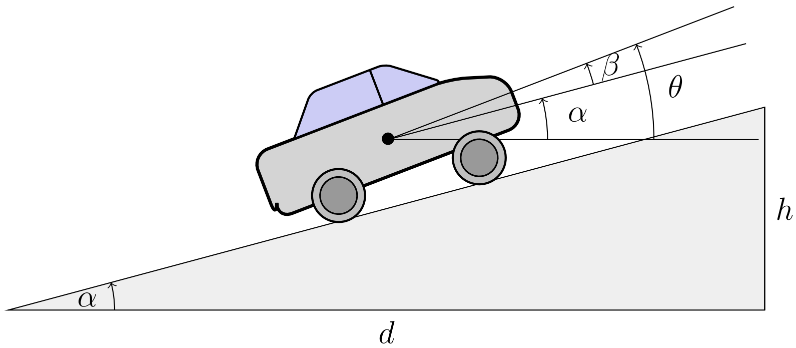

Figure 5.4: Car driving on a ramp. Due to forward acceleration the car tilts back.

5.2 IMU + Odometer

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5.3 LiDAR only

5.4 All other fusion stuff

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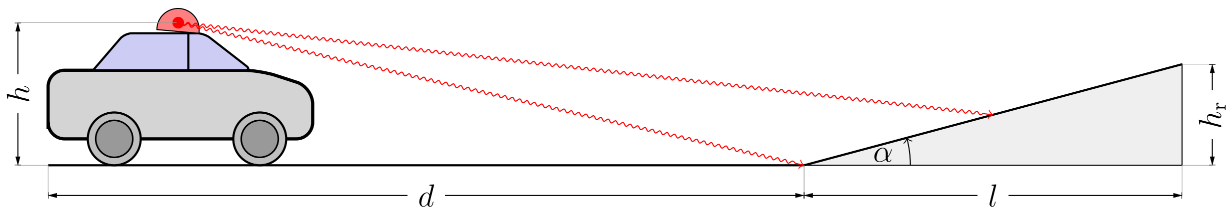

Figure 5.5: Tikz is hard

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5.5 Validation Concept

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Chapter 6

Results

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Chapter 7

Conclusion

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Chapter 8

Appendix

Code extracts and extra plots etc