Using Crowdsourced sensor networks to gather up to date information on deformations of road networks

by B.R. Ligtvoet

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First supervisor: Ir. E. Verbree (Edward)

Second supervisor: Dr.ir. B.G.H. Gorte (Ben)

1 Introduction

1.1 Research goal

The goal of this research is to test the extent to which crowdsourced sensor network data gathered by having people drive across a road pavement asset, can be used to monitor the current state (1.1) and the changes of an asset through time (1.2). This information can then be used to for example: add a change in the maintenance plan, make a decision to do nothing based on the data, schedule an inspection, or learn more about the features of the Dutch road network. The role of smart and efficient maintenance has increased due to the rise in popularity of Design, Build, Finance and Maintenance (DBFM) contracts in the building sector (Pohl, Schenk, & Bilt, 2013). The potential of using crowdsourced sensor networks lies in the fact that 81% of the people in the Netherlands own a smartphone containing the necessary equipment, making them a possible "inspector" of the state of the assets they drive across each day (de Bruyckere, 2015). The geometry of the road influences the microelectromechanical sensors such as the Inertial Measurement Unit (IMU) in the smartphones of the road users. The data can be gathered to possibly monitor the state of the road, as well as the history without the need to employ extra professional inspectors.

Figure 1.1: A possible area of interest for profile reconstruction.

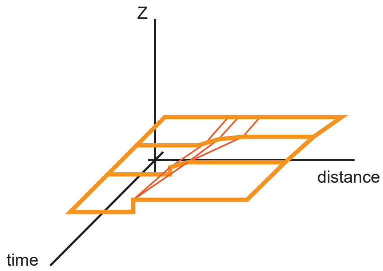

Figure 1.2: The results of the profile geometry with the Z axis showing the changes in height of the embankment set against time and distance

1.2 Research question

To what extent can the current state and the degradation of road pavement be measured by crowdsourced sensor networks?

1.2.1 Sub Questions

Is it possible to monitor the current state of a road section with consumer grade MEMS sensors?
Which road network phenomenon can be detected using the crowdsourced sensor network?
What information and data is needed to monitor the road pavement?
What factors influence the accuracy of the crowdsourced sensor network?

What are the effects of having constant low accuracy measurements on the calculation used to monitor the state of an asset?
How can the information be linked to an existing asset?

1.3 Relevance

1.3.1 The relevance of collecting data with crowdsourced sensor networks

The integration of IMUs into objects we take with us when travelling enables the scanning of large parts of the road infrastructure with a smaller investment when comparing to specialised inspections as they cost man hours as well as expensive hardware such as the specialised ARAN. On the other hand data gathered from IMUs in smartphones of many people is reliant on the existing vehicles or users travelling on a road, but require less investments as the hardware needed for measurement does not need to be purchased. However one of the key challenges is to convince people that participation in a crowdsourced sensor network is beneficiary. The raw data which is gathered by the crowdsourced sensor network can have multiple uses, next to the use of contractors: road users might also benefit from knowing the status of the road; the real time data from the network might be usable for monitoring the flow of traffic, causing less congestion; the information can also be relayed back to the drivers informing them of optimal speeds.

1.3.2 Commercial relevance

The importance of carrying out performance based maintenance is increasing. The construction market is introduced to Design, Build, Finance & Maintain (DBFM) contracts and the railway sector is increasingly often using Performance Based Contracting (PBC) for their maintenance contractors (Leijten & Koppenjan, 2010; Pohl et al., 2013). With DBFM contracts the contract value is decided up front and the contractor has to finance both the construction and the maintenance, shifting the risks to the contractor. Efficient planning allows for repairs to be done at the least costly times of the day and week, reducing maintenance costs. In PBC the contractor is obliged to provide a certain amount of availability instead of maintenance, which is linked to financial repercussions when the obligations are not met. In both situations monitoring the performance of assets can be used to gain knowledge on when assets need maintenance, which in turn enables for more efficient planning and strategic decision-making regarding maintenance activities.

1.4 Abbreviations

ARAN = Automatic Road ANalyzer
DBFM = Design, Build, Finance & Maintain
DCM = Direction Cosine Matrix
GNSS = Global Navigation Satellite System
GPS = Global Positioning System
HRI = Half-car Roughness Index
IMU = Inertial Measurement Unit
IRI = International Roughness Index
LIDAR = LIght Detection And Ranging
MEMS = Microelectromechanical System
MLS = Mobile Laser Scanner
PBC = Performance Based Contracting
PS-InSAR = Persistent Scatter Interferometric Synthetic Aperture Radar
RWS = Rijkswaterstaat
TLS = Terrestrial Laser Scanner
UAPS = Unmanned Aerial Photogrammetric System
UAV = Unmanned Aerial Vehicle

2 Related work

Through the years there have been many different techniques which were used to monitor the state of a road network asset. To identify the added value of IMU data generated by crowd-sourced sensor networks, first the values of the currently used techniques need to be defined. This chapter is therefore focused on identifying the techniques used during inspections, and their pros and cons. Next the place of large scale user generated IMU data will be discussed in relation to these techniques.Finally several applications of VGI in relation to vehicles and positioning are discussed.

2.1 The current state of road network asset inspections in the Netherlands

The Rijkswaterstaat (RWS) has defined different types of inspections which are performed to monitor the state of the Dutch road network assets (Rijkswaterstaat, n.d.; Schultz van Haegen, 2016). The most often done type of inspection is called the 'dagelijkse schouw' which translates to daily inspection, it pertains a drive-by inspection by eye on the traffic flow and general safety of assets. Next is the so called 'toestandsinspectie' which is a yearly activity to check less often used assets. The least often used inspection is called 'visuele inspectie' which is performed each 6 years. In for example the case of bridges this pertains the thorough inspection of all assets which are part of the bridge construction as well as an assessment on the alignment of the current function of the bridge and its designed function. For road network inspections RWS also makes use of an Automatic Road ANalyzer (ARAN) which scans each highway road section once a year Lub (2016).

Figure 2.1: The ARAN of RWS in action). (Rijkswaterstaat, 1996)

2.2 Technologies in road network monitoring

There are many different technologies which can be used to monitor the surface of road networks, some of which are equipped on the ARAN. This section describes the technologies of laser scanning § 2.2.1, photogrammetry § 2.2.2, PS-InSAR § 2.2.3, Inertial Profilers § 2.2.4 and user generated IMU data § 2.2.5

are discussed in this section. For each technology research is presented which shows the use of the specific technology in the field of road network monitoring.

2.2.1 Terrestial and Mobile Laser Scanning

The usage of laser scanning as a way to garner information about the state of the road network is gaining in popularity; the data form laser scanners can be used to create dense point clouds of the road network and the environment around it (Guan, Li, Yu, Chapman, & Wang, 2015; Kim et al., 2001). There are two system which are used most often to scan road networks: Mobile Laser Scanners (MLS) and Terrestrial Laser Scanners (TLS). Terrestrial Laser scanners are static, and need to be moved by hand to a new location after it has finished scanning its current location. Mobile Laser Scanning is performed by a vehicle equipped with laser scanners as well as other sensors needed to identify its own position. Mobile laser scanning can be performed at speeds acceptable for highways, enabling the capture of long stretches of road (Guan et al., 2015). Using a MLS also removes the need to close down stretches of road as with TLS (Kim et al., 2001).

The research done by Guan et al. and Kim et al. use these different methods of using laser scanners to collect data. Road fractures are the most common asphalt concrete-surfaced pavement distress. Guan et al. use an MLS consisting of a GNSS, an IMU integration system, laser scanners and high resolution cameras to extract these fractures as well as the road markings. The point cloud generated form the data is analysed to detect the road area by using planar surface detection, pattern based classification, intensity and signal. Curbs are used as a recurring pattern which indicates the boundaries of a road area (figure 2.2). The identified road area is processed by a prototype algorithm to detect markings by finding areas with high reflectivity, road fractures are identified by their low contrast, low signal-to-noise ratio and poor continuity.

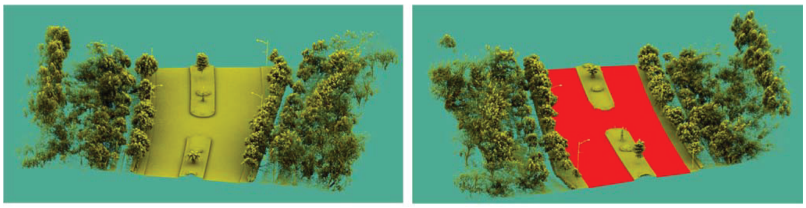

Figure 2.2: The raw Mobile Laser scanner data (left) and the resulting extraction of the road area(right). (Guan et al., 2015)

On the other hand there is the research from Kim et al., where the data gathered form the TLS is used to extract the road centreline, slope, cross slope and the geometry of nearby features such as the barriers next to the road. A TLS is a less complex machine compared to an MLS, however there are also downsides to using a TLS: a TLS will make a new point cloud for each change in location, connecting these point clouds into one point cloud requires the use of reference points.

2.2.2 Photogrammertry

Aerial photogrammetry is not commonly used to gather data about the state of the road network. This is due to the lower accuracy of a point cloud generated from photogrammetric data (Díaz-Vilariño, González-Jorge, Martínez-Sánchez, Bueno, & Arias, 2016). However as shown by Díaz-Vilariño et al., there are uses for photogrammetric imaging. The decrease in costs due to the developments in the field of Unmanned Aerial Vehicles also makes the technique interesting: the photogrammetric survey can be automated by designing a flight plan the UAV will adhere to and consumer grade cameras can be used to collect the images (Remondino, Barazzetti, Nex, Scaioni, & Sarazzi, 2011).

Díaz-Vilariño et al. used UAVs to collect data on a road section in Italy. The goal was to test the usage of an Unmanned Aerial Photogrammetric System (UAPS) for calculating road runoff. The images collected by the (UAPS) were converted to a DEM from which the road runoff direction was calculated by using the commonly used D8 algorithm. It was concluded that data form UAPS data with cell resolutions higher than 2 meters, will return the same result as data from a LIDAR system 84% of the time. A downside of using photogrammetry in combination with a UAV is that there are stick rules on where a UAV is allowed to fly, as well as the limited battery time and the small weather window suitable for operations (Díaz-Vilariño et al., 2016).

2.2.3 PS-inSAR

PS-InSAR is a technology which uses an archive of satellite images to determine deformation based on changes between the individual images or an image series though time (Gehlot, Ketelaar, Verbree, & Hanssen, 2005). PS-InSAR can be used to monitor changes to surfaces, and one of its main advantages is that it can monitor large areas with a high temporal resolution compared to more conventional techniques, due to the constant data gathering from satellites. PS-InSAR makes use of Persistent Scatter (PS) points which are selected based on their amplitude, phase and time series coherence, these points have a high temporal consistency are often connected to manmade buildings (Wu & Hu, 2015). These PS points are used to cope with incoherences caused by for example changing landscapes though the seasons. As Wu and Hu show, PS-InSAR can be used to quickly detect areas of the road network with high subsistence (figure 2.3). However as Gehlot et al. note, the deformations registered with PS-InSAR have different causes. The correct identification of the cause of subsistence has an impact on the meaning of a piece of data.

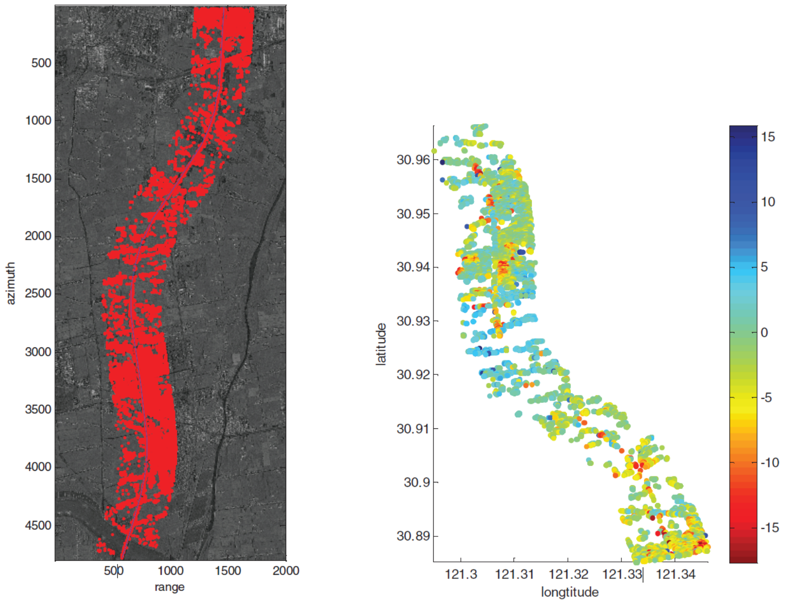

Figure 2.3: The selection of Persistent Scatter points (left) and the settlement results(right). (Wu & Hu, 2015)

2.2.4 High Speed Inertial Profilers

High Speed Inertial profilers are capable of being deployed at the speeds needed to drive over a highway without causing mayor danger to other drivers. These inertial profilers are used to measure the International Roughness Index (IRI). The IRI is calculated from the accumulated suspension movement from a Golden Car over a profile (Bridgelall, 2014). The Golden Car is a quarter car, which mean that it only takes into account the suspension form one car wheel. The speed for an IRI calculation is set to 80 km/h due to the fact that the results of the IRI are speed dependent (Gillespie, 1981). By setting the speed for the IRI to 80 km/h, the comfort level in a car at normal driving speed on a highway can be calculated. RWS makes use of the Half-car Roughness Index (HRI) to measure comfort in the Netherlands. The HRI takes the average suspension movement of two wheels, however RWS is researching whether they can move from HRI to IRI (Lub, 2016, Annex I, A4) . The downside to using High Speed Inertial Profilers is that different runs across the same road section will lead to a shift in location due to GPS inaccuracies (Fujino, Kitagawa, Furukawa,

& Ishii, 2005).

2.2.5 Volunteered Geographical Information and IMU data

User generated IMU data can be gathered from either smartphones, or directly from the car when working together with manufacturers (Waite, Walsh, & Garcia, 2012). The usage of lower cost and lower precision measurement equipment is researched by multiple people, and advancements are being made. From showing the correlation between the root mean square of the accelerometer data with the road geometry (Fujino et al., 2005), to calculating a horizontal and vertical accuracy (Karamanou, Papazissi, Paradissis, & Psarianos, 2009), the usage of smartphones to calculate the HRI with a standard deviation between the 0,23 and 0,26 m/km (Lub, 2016) and finally, using smartphones to calculate the IRI of a large length of road (Forslöf & Jones, 2015).

Karamanou et al. (2009) showed that an GPS/IMU system can be used to calculate the profile of large stretches of road (figure 2.4). The system used for the research analyzed 600 KM of road network in Greece. The results showed that the vertical accuracy was on average around 10 cm. Lub (2016) researched whether the IMUs in smartphones could replace the ARAN vehicle from RWS. Currently both industries and government organizations from other countries are trying to discover the possibilities of user generated IMU data (Waite et al., 2012). The results from citetLub2016's research showed that the smartphone data could not be used to replace the ARAN. However the use of this technology can be used to fill the gaps in between the high precision inspections, proving are more constant insight into the current status of road networks. The use of smartphone sensor data as a support system to high quality, high cost data acquisition is also defined by Forslöf and Jones (2015) as an area of potential for the technology. However Forslöf and Jones also notes that the technology can also be used to give early warnings of changes, provide constant monitoring possibilities and trend description. Road roughness calculated from smartphone data cannot replace high precision profiles, but it can be used to give subjective ratings of road comfort.

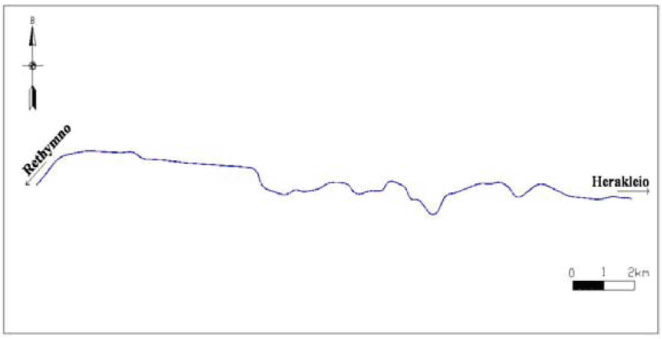

Figure 2.4: The vertical profile of a road between Rethymno and Herakleio computed from IMU data. (Karamanou et al., 2009)

2.3 Other uses for crowdsourcing in transport networks

There are many applications for crowdsourcing and the user as a sensor, this section will shortly describe some of the research done in the area of automobiles and positioning. Jin, Han, Liu, and Feng (2015) uses crowdsourced Volunteered Geographical Information (VGI) to identify unwanted behaviour of taxi drivers, namely Taxi Passenger Refusal (TPR), which is describes as the act of refusing passengers after enquiring and knowing the travelling destination considering the economic benefit. On the other hand Renganathan and Velaga (2016) uses data from cars which have driven across a road to inform the cars which come after about the road condition. Finally, Qin et al. (2015) uses VGI to gather information about obstacles to improve spatial services for disabled people.

Jin et al.'s research is focussed on combining the automated gathering of Positioning data with passenger experiences. TPR is a problem in large cities, however the threshold of reporting a TPR too high for passengers and they often do not bother reporting it. Gathering proof of a TPR is also difficult for authorities. Jin et al. uses the GPS data form both the taxi and the potential passenger and analyses both to detect abnormal behaviour. The act of a TPR can be described as the nearing of the taxi to the potential passenger, next the taxi slows down. If the taxi proceeds to drive away from the potential passenger, a TPR has occurred. By using this information together with Human Intelligent tasks, the feedback from denied passengers can be connected to the evidence of the taxi driving away.

Renganathan and Velaga describes in his work a theoretical system in which information from cars driving on a road can be shared with drivers who use the same road at a later time, informing them about the quality and condition of the road. The research makes use of the Internet of Vehicles, an offshoot of the Internet of Things where vehicles are able to constantly communicate with each other. The data is gathered by rash driving sensors, ABS deployment sensors, orientation sensors and the positioning system in the car. This data is sent to a server where it is analysed to gather information about the quality of the road, the information is then shared with all the other cars in the area. The main focus of Renganathan and Velaga's is on the identification of valid data; the data gathered form the rash driving sensor might not always indicate a bad road quality, but a bad driver.

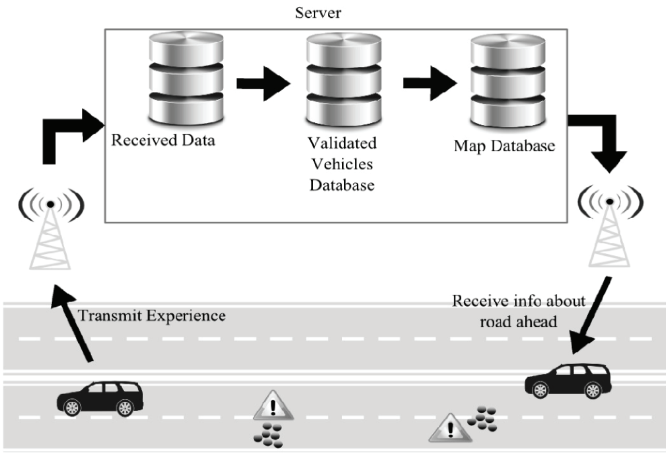

Figure 2.5: Design of a system to share passenger experience with other cars on the road. (Renganathan & Velaga, 2016)

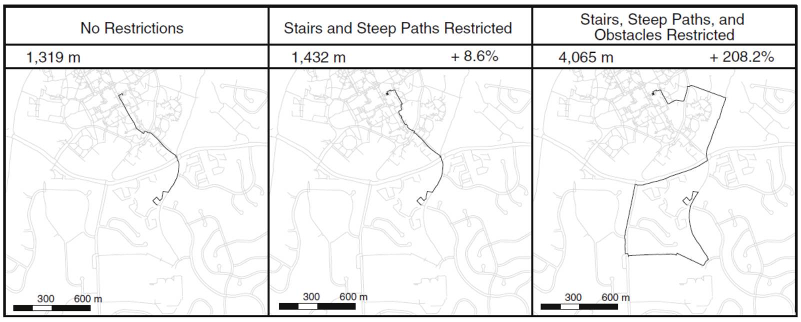

Figure 2.6: Different possible routes to a location on the George Mason University campus, Fairfax. The first route has no access restrictions (left), the second route is calculated to not include stairs and steep paths (middle), the third route excludes stairs, steep paths and obstacles. (Qin et al., 2015)

Qin et al. uses VGI and crowdsourcing to improve accessibility and routing services for disabled people. The test location used in the research is the George Mason University Campus in Fairfax, USA. One of the problems for disabled people is that they are dependent on static accessibility maps while many obstacles are transient in nature. These transient obstacles change the pedestrian routes in a day to day way, making it difficult to have an up-to-date accessibility map of the campus. By using VGI provided by students and people on the campus, the accessibly maps can be more temporally accurate. Volunteers can mark locations which are blocked by obstacles, they can add a description as well as an estimation of duration of the obstacle. These obstacles are used to redefine the network used for routing. Different networks are created to accommodate people with different disabilities (figure 2.6). Qin et al. notes that one of the other possible applications is the identification of areas which are highly inaccessible. However there are also downsides of relying heavily on the input of volunteers, namely the quality and reliability of the information provided by the volunteers.

3 Research objectives

3.1 Scenario

An asset manager named John at construction company GoodMaintain is planning the new maintenance schedule for the coming months. There are many planned maintenance jobs in the pipeline, crowding the schedule. Because of the almost fully booked schedule , John cannot afford sudden extra work. Fortunately John still has two timeslots left to fix possible failures. John decides to look on the asset management dashboard where he can check the performance of all the assets he needs to manage. Due to constant monitoring done by consumer cars and telephones, He can see the roughness off the different road sections and other assets embedded in the road.

John filters the assets to focus on bad road sections. Deciding to take a better look on a rough section near the embankment of a bridge, John can see the longitudinal profile of the asset. He sees that the loose ground around the embankment has set, and that a height difference has been growing since the last maintenance work, two years ago. However, the height difference together with the slow growth speed does not warrant an immediate repair. He decided to make a note to schedule a maintenance crew for another month when the schedule is less crowded.

Next John checks an asset near an expansion joint in a tunnel. He sees that a hole is forming near the joint over the last month. John decided that a repair is warranted before the problem becomes more severe. He plans the maintenance for the earliest empty slot in the schedule. Over the coming months John will keep monitoring the expansion joint to see if it is within acceptable working parameters until the maintenance work is performed. Meanwhile the consumers in the Netherlands are able to use a high quality road network, without being constantly hindered by sudden emergency repairs. However there are also different strategies on how to react to the provided information. John can also use the information to gain more knowledge on how the Dutch road network degrades, for which there is currently little information as mentioned by Klunder et al. (2010).

3.2 Scope

The focus of the research is on the analysis of a large amount of low accuracy data. The locational focus for the research will be the Dutch highway network, this is due to the general smoothness of the asphalt, which gives a large contrast between situations where the pavement is damaged or has settled over time and a situation where the pavement is intact. There are two different levels in positioning accuracy which will influence what type of damage will be detectable: highway-wide and lane. Highway-wide can be used to detect settled pavement, while the lane location can be used to possibly detect smaller damage such as surface damage. The analysis will prove to what extent both types of damage can be detected with the low accuracy smartphone sensors, however the actual lane detection phase will not be part of the research.

The low accuracy data will be gathered during the research by using smartphone IMUs and GNSS. While the resulting dataset might be relatively small compared to an actual crowdsourced sensor network, the data will contain multiple runs which shall be used to investigate the effects of the increasing amount of data on the information on the state of the road. Lub (2016) and Klunder et al. (2010) remark that the information gathered form the IMU data is not meant to, and cannot replace measurements from specialised vehicles. Rather, the crowdsourced sensor network can be used as an extra source of information to possibly identify problem areas with a higher time resolution, as well as be used to identify places where preventive maintenance can be performed.

This research does not cover an extensive adoption of the software needed to gather data, nor the creation of an application to gather this data. Instead premade software is used for data gathering.

3.3 Research methodology

The research methodology consists of four main steps: establishing data requirements, data gathering, analysis and data storage (figure 3.1). These methodology for these steps is described in subsections § 3.3.1,§ 3.3.2,§ 3.3.3 and § 3.3.4.

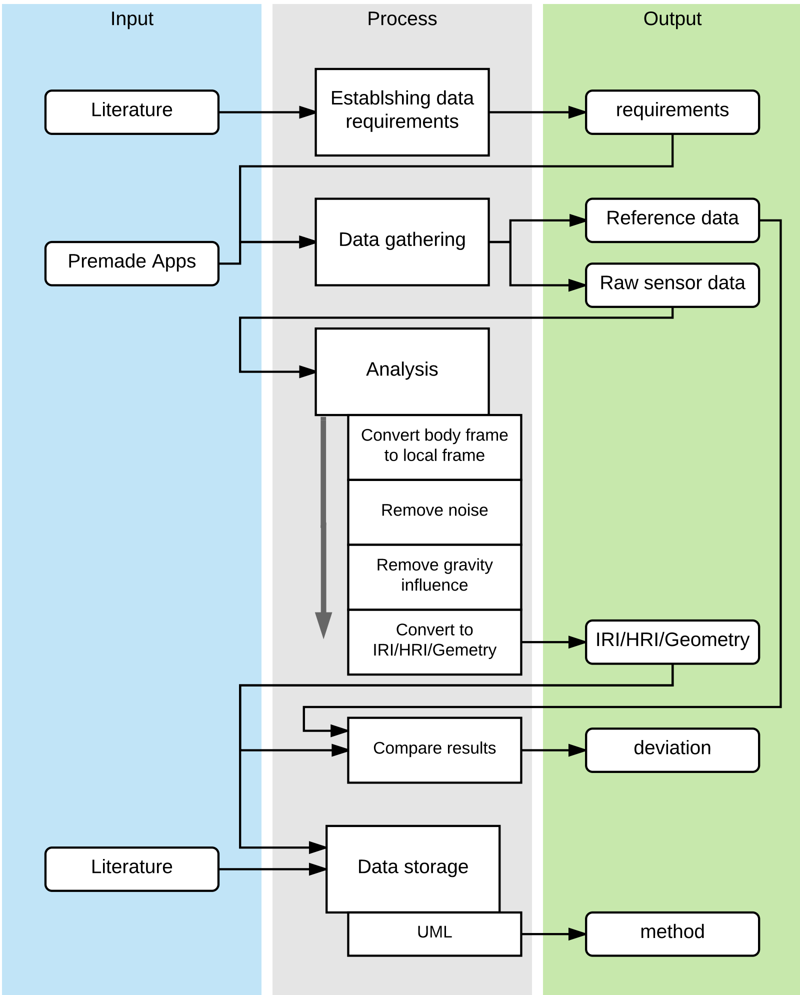

Figure 3.1: A flowchart of the research process

3.3.1 Establishing data requirements

Before any data can be gathered on the state of a road network asset or a road section, the requirements for the raw data need to be set. This is covered with the sub question: What information and data is needed to monitor the road pavement? These raw data requirements need to be set before measuring to prevent a misalignment between the available data and the requirements from the methods which will be used to analyse, and return information on the state of the road. Both Lub and Karamanou et al. use a GPS/IMU combination for measurements, though Lub uses smartphones and Karamanou et al. use specialised equipment.

Two of the important methods for measuring the longitudinal profile of the road are the IRI, the international standard, and the HRI, the standard currently in use by RWS (Lub, 2016). Another option is to use the geometry of the displacement to monitor the road, which compared to IRI and HRI is not absolute and might be usable to see the difference between holes and bumps. The factors which influence the displacement and acceleration are the speed of the car, the weight and the suspension. The location of the phone is also needed to later connect the data or information to an asset.

3.3.2 Data Gathering

The data gathering phase consists of choosing locations based on what phenomenon needs to measured, and how it will be measured. As mentioned in section § 3.2, the focus of the research is on measuring ground settlement and holes. A location will therefore need both of these phenomenon. While the locational focus of the research is the Dutch highway system for its smoothness, local roads are an option for gathering data. Local roads in the Netherlands are oftentimes also paved with asphalt and are much better accessible for multiple test runs and measurements outside the vehicle. Data from two different locations is needed to assess whether or not smartphone sensors can be used to detect changes trough time. If the raw sensor data shows, after analysis, a difference in geometry can be used to show that the data can be used for historical monitoring.

The data will be gathered by an app on a commercial smartphone. During the research a premade app will be used which provides the raw sensor data. By using a premade app like Sensor Data Streamer or SensorLog development time is saved (FNI Co., 2013; Thomas, 2016). A downside to using premade apps is that they might not provide the necessary data defined in the requirements phase (subsection § 3.3.1).

3.3.3 Analysis

Convert body frame to local frame

One of the features of using a smartphone as a measurement device is that its body frame can be moved around and reoriented. In the case of many devices this will mean that all these individual smartphones will be measuring the road from many different angles and orientations (figures 3.2 and 3.3). To combine these data streams from different devices, a transformation from their body frame to a local reference frame is necessary. A often used method in positioning is the use of the IMU data to create a Direction Cosine Matrix (DCM) (Ibrahim & Moselhi, 2016; Renaudin & Combettes, 2014; Zheng, Han, Yue, Yuan, & Wo, 2016). This DCM can be used to transform the accelerometer data to the same local reference frame after which it can be compared or combined with the other data streams.

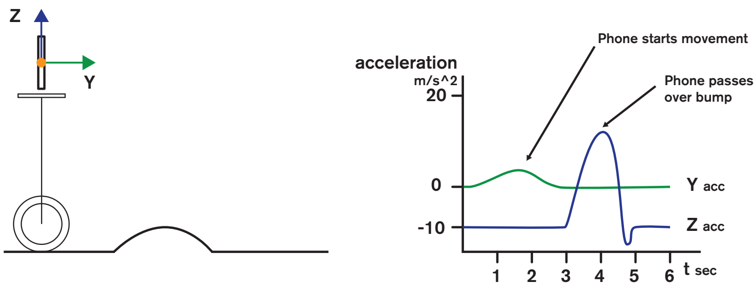

Figure 3.2: Conceptual acceleration data without noise from a smartphone oriented perpendicular to the earth's surface. Road geometry can be seen on the left, the conceptual acceleration measurements are on the right.

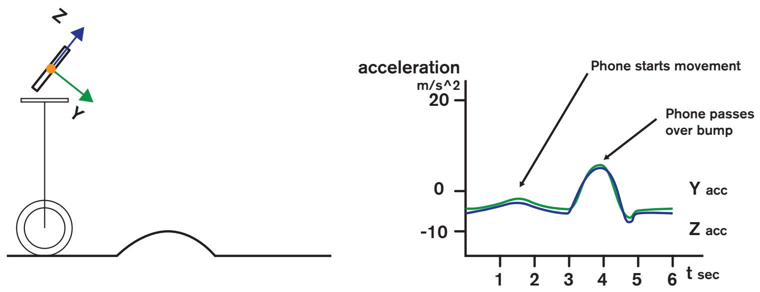

Figure 3.3: Conceptual acceleration data without noise from a smartphone tilted approximately 45 degrees. Road geometry can be seen on the left, the conceptual acceleration measurements are on the right.

Remove Noise

Every sensor experiences noise, in the case of smartphones the noise is caused by the low accuracy of the sensors needs to be removed. There are different methods of removing the noise, oftentimes a Kalman filter is used (figure 3.4), though a low pass filter is less complicated and can also be used (Bruwer & Booysen, 2015; Cízek, Wolfgang, & Weron, 2005; Grewal, 2011).

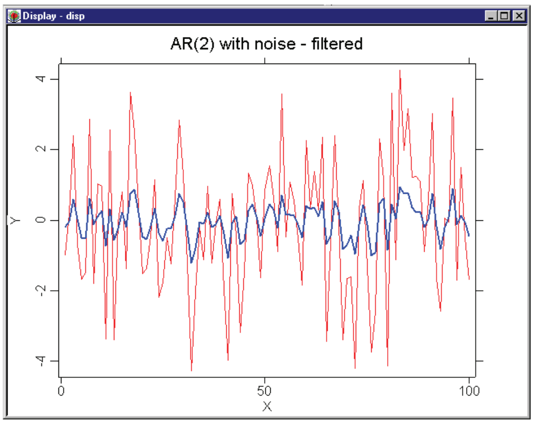

Figure 3.4: The smoothing effect of a Kalman filter on example data (Cízek et al., 2005).

Remove gravity influence An accelerometer in an IMU constantly measures the gravity the earth is exerting on it (Sayers & Karamihas, 1998). This constant gravity also affects the measurements. To ensure that gravity does not affect the measurements in the Z-axis, the vertical acceleration, it needs to be removed. Ibrahim and Moselhi (2016) propose to use the derivative of acceleration, jerk, to remove the gravity factor as well as any DC bias the sensor might have.

Convert to IRI, HRI or geometry

Before converting to either IRI, HRI or geometry, the displacement has to be calculated by integrating jerk to acceleration with the trapeize integration method as described by Ibrahim and Moselhi (2016). The next two sets of integrals are velocity and then displacement. The GNSS coordinates calculated by the smartphone can be enriched with the displacement data in the X and Y axis to give the most likely actual location of the phone with an extended Kalman filter which is often used in positioning to combine data from multiple sensors (Gao, Liu, Atia, & Noureldin, 2015; Rose, Britt, Allen, & Bevly, 2014). The vertical data from the GNSS will not be used since the absolute height is not of interest when detecting holes or settling ground. Now that the height per most likely location is known, the conversion to either IRI, HRI or road geometry can be made.

Up until this point all analysis took place on data which described the movement of the smartphone. The Golden Quarter Car is a description of the suspension on one wheel of the most average car. The suspension data from the Golden Quarter Car can be used to calculate the displacement of the wheelbase. From this data the HRI and IRI can be calculated through a program named ProVal (PROVAL, 2016).

3.3.4 Data storage

To make data retrieval easier for the contractor, it is beneficial to connect the information to the asset it pertains. By doing this a system can be created where the contractor can select an asset which can be used to query for the intended information. An alignment between the attributes of the information and the attributes of the asset is needed. One of the challenges in this situation is that positioning data can differ from the actual measured location, though the effect is decreased by using the extended Kalman filter as described in subsection § 3.3.3. A possibility would be to use an offset of the asset geometry bounds to query the data, though literature will be consulted for any customary ways of querying spatial data based on another type of spatial data.

4 Planning, tools and data

Month	Period	Activity
January	First half	P2
	Second half	- Set data and information requirements
		- Prepare for data gathering
February	First half	- Choose location
		- Data analysis methods research
	Second half	- Gather data at location
		- Data analysis - DCM
		- Data analysis - remove noise
March	First half	- Data analysis - remove noise
		- Data analysis - remove gravity
		- Data analysis - combine GNSS and acceleration
	Second half	P3: Colloquium midterm
April	First half	- Theoretical storage design
		- validate
	Second half	- Writing report
May	First half	- Writing report
	Second half	P4: Formal Process Assessment
June	First half	- Writing report
	Second half	P5: final assessment

4.1 Meetings

Meetings will happen biweekly with both Edward Verbree, the first mentor, and Ben Gorte, the second mentor. There is a possibility that the research will be performed at Volker Infra, in which case Martinus van de Ruitenbeek will act as an advisor.

4.2 Tools

Measurement tools:
Sensor Data Streamer app by FNI Co., LTD., which requires a computer to receive the data through the UDP protocol.
Sensor Data app by Wavefront Labs, which can both save the raw data to a csv or stream it live.
No decision has been made on what tool to use to gather reference data of the location for the validation of analysed accelerometer data.

Analysis tools:
Programming will be performed in either Matlab or Python. The choice will be made on the built in support for the Kalman filter, DCM and error removal. The inbuilt mathematical functions and plotting methods in Matlab make it the most likely candidate currently.
ProVAL, an IRI calculation progam. It is free of costs and can be downloaded at
http://www.roadprofile.com/proval-software/current-version/. Proval uses several different file

formats specialized for road monitoring, loading the analysed data will require a conversion to one op the supported file formats.

Tools for storage:
UML Class diagram
PostgreSQL

4.3 Data

The data used during this research will be gathered with smartphone apps. No decision has been made on how to gather data of the test location needed for validation. An option is to study the new Actueel Hoogtebestand Nederland 3 for which pointcloudfiles can be downloaded from https://www.pdok.nl/nl/ahn3-downloads.

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