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Abstract

This literature study analyses the state of the art in the application of satellite navigation in the intermodal transport process. After a short introduction, intermodal transport and its elements are explained in chapter two. This includes explaining the standard container, the most common transportations methods, and the harbour. The study continues in chapter three with exploring the types of satellite navigation including GPS, GLONASS, BeiDou, and Galileo. Chapters two and three come together in the fourth chapter where an analyses of the current and future state of applications of satellite navigation in intermodal transport is discussed. Currently satellite navigation is mostly used as a tool for humans to control vehicles, where in the future the information of the navigation systems is directly used by computers to determine optimal routes and avoid accidents. The study ends with a conclusion in which the current and the future state are compared.
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Chapter 1

Introduction

Where the economic consequences of the 2009 will still be felt for a long time, the port transport of containers was within a year already higher than ever before (see figure 1.1). This growth, partly caused by globalization and the opening of new sales markets in developing countries, shall continue for the foreseeable future and is more likely to increase then decrease any time soon. Although there is therefore a great demand for container transport, there is also demand for more effective and environmentally-friendly transport at the same time. This is in no small part due to the higher fuel costs and stricter legislation. A large part of making transport more effective is improving routes and responding better to changes in these routes. To do this, satellite navigation is already widely used to determine routes with precise locations and speeds. Another role for satellite navigation to play is in the tracking and tracing of cargo. Tracking and tracing enables a customer to know where the cargo is and where it has been, information that can be used to make an estimated arrival time. This same system is used to give the sender confirmation when the cargo has arrived. The first such systems used manual check-lists at various points in the processes, such as harbours. Current systems mostly use bar-codes to directly relay the information to a digital system. While this system is fairly efficient, information on the cargo is only known at specific locations. To have a more complete overview of the transport of cargo, there is sometimes made use of GPS-trackers to determine the real-time location. This information is also used by the shipping companies for monitoring the cargo, since by knowing the location of the cargo at all times, theft and lost cargo can be prevented. This literature study will focus on the question:

Where is satellite navigation applied in intermodal container transport and where will it be applied in the future?

To answer this main question the following sub-questions will be answered:
• What is intermodal transport?
• What is satellite navigation?
• What is the state of the art in the application of satellite navigation in intermodal transport?
• What new technologies are in development for satellite navigation in intermodal transport?

These questions will be answered by searching research-papers, books, government websites but also corporation websites.

1.1 Structure of the report

The results found in these sources will be presented in four parts. In the first part the complete intermodal transport process, of which maritime container transport is part, is described. This includes the different kinds of modes, but also tracing tracking and monitoring of cargo. The report continues in the second part, with a focus on satellite navigation, its workings and the different types of systems. In the third part the current and future application of satellite navigation in each of the modes of intermodal transport are discussed as well as the application in tracing, tracking and monitoring. The report shall end with and conclusion in which the found applications are shortly discussed.
Chapter 2
Intermodal freight transport

Over the years there have been many different definitions of the term intermodal transport, as can be seen in Table 2.1. While there was a proposal for a unified definition by the European Conference of Ministers of Transport and United Nations in 1997 this was not commonly accepted since it only covers the physical and not the organisational part of intermodal transport [10]. Most sources do agree that in intermodal transport a container, trailer or otherwise standardised unit is used to move cargo over multiple transport modes without handling the goods themselves. The most common standardised unit is the twenty foot (equivalent) container (TEU). Using TEU’s improves the transport process greatly, since the use of one standard enables the use of specialised/optimised equipment for speed and effectively. This also enables a fast transition between transport modes. A quick transition is needed since to get freight from place A to place B sometimes up to five different transport modes. In the next sections an overview of these modes, and their relations to each other and the TEU’s is given.

2.1 Modes of intermodal transport

2.1.1 Truck

Most of the time (container) trucks are the first and the last step in the transport of containers. This because where ships are limited to waterways and trains to railways but roads are virtually everywhere. The effect of this is that in the most countries the main part of inland transport happens over the road. As can be seen in Table 2.2 the only exceptions to this rule in Europe are Estonia, Latvia, and Lithuania where transport over rail is the largest form of transport.

Since time in the docks is expensive it is imperative that the trucks carrying the container arrive on time to prevent any delays. On the other hand, arriving too early means that the containers need to be stored on site, which, while not as expensive as delaying a container ship, is also pricey. The result is this is that precise schedules and routes need to be made, especially when considering that the port can only handle a certain number of trucks per hour. This is to prevent congestions and reduce CO₂-emissions. [14] Not all cargo is large enough to fill a TEU, therefore the cargo of multiple shipments with destinations close to each other is often combined in a distribution centre to be sent as one. The TEU is then sent to a distribution centre near the destinations where it is unpacked and distributed. These distribution centres use trucks to transfer the unpacked cargo to their end-destinations, and to pick up cargo that is to be send. To do this effectively distribution centres make use of fleet planners which task it is to optimise the route for multiple trucks (a fleet). The problem to be solved is commonly known as the travelling salesman problem or principle. The travelling salesman problem is used to calculate the most efficient route when a salesman (in our case truck) needs to visit multiple customers (in our case delivery or pick-up points) and return to a depot (in our case this is often the distribution centre). The travelling salesman principle is one of the most famous optimisation problems, especially since it is an NP-hard problem. The more "customers" the travelling salesman problem has the longer the computational times. [15] Since trucks cannot transport infinite cargo, but have a limited capacity, the trucks have to return to the distribution centre to refill. This makes the problem a Truck Dispatching Problem which is a generalization of the Travelling salesman problem. An example of this and a possible solution can be seen in Figure 2.1. Figure 2.1a shows the problem: A distribution centre in the middle of a city grid (roads are drawn in grey), which has to dispatch two trucks to deliver good to the nine stores in the neighbourhood. [16]. To solve this problem the location of the pick up and delivery points
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jones et al, 2000</td>
<td>The shipment of cargo and the movement of people involving more than one mode of transportation during a single, seamless journey.</td>
</tr>
<tr>
<td>Southworth &amp; Peterson, 2000</td>
<td>Movement in which two or more different transportation modes are linked end-to-end in order to move freight and/or people from point to origin to point of destination</td>
</tr>
<tr>
<td>Min, 1991</td>
<td>The movement of products from origin to destination using a mixture of various transportation modes such as air, ocean lines, barge, rail, and truck.</td>
</tr>
<tr>
<td>Schijndel, 2000</td>
<td>The movement of cargo from shipper to consignee using two or more different modes under a single rate, with through billing and through liability (Hayuth, 1987).</td>
</tr>
<tr>
<td>D’este, 1995</td>
<td>A technical, legal, commercial, and management framework for moving good door-to-door using more than one mode of transport.</td>
</tr>
<tr>
<td>Ludvigsen, 1999</td>
<td>The movement of goods in the same load-carrying unit, which successively use several transport modes without handling of goods under transit.</td>
</tr>
<tr>
<td>Tsamboulas &amp; Kapros, 2000</td>
<td>The movement of goods in one and the same loading unit or vehicle, which uses successively several modes of transport without handling the goods themselves in changing modes (European Conference of Ministers of Transport, 1997).</td>
</tr>
<tr>
<td>van Duin &amp; van Ham, 1998</td>
<td>The movement of goods in one and the same loading unit or vehicle, which uses successively several modes of transport without handling the goods themselves in changing modes (European Conference of Ministers of Transport, 1997).</td>
</tr>
<tr>
<td>Murphy &amp; Daley, 1998</td>
<td>A container or other device which can be transferred from one vehicle or mode to another without the contents of said device being reloaded or disturbed (Jennings &amp; Holcomb, 1996).</td>
</tr>
<tr>
<td>Newman &amp; Yano, 2000a, 2000b</td>
<td>The combination of modes, usually ship, truck or rail to transport freight.</td>
</tr>
<tr>
<td>Taylor &amp; Jackson, 2000</td>
<td>The co-ordinated transport of goods in containers or trailers by a combination of truck and rail, with or without an ocean-going link (Muller, 1995).</td>
</tr>
<tr>
<td>Slack, 1996</td>
<td>Unitised loads (containers, trailers) that are transferred from one mode to another.</td>
</tr>
<tr>
<td>Spasovic &amp; Morlok, 1993</td>
<td>The movement of highway trailers or containers by rail in line-haul between rail terminals and by tractor-trailers from the terminal to receivers (termed consignees) and from shippers to the terminal in the service area.</td>
</tr>
<tr>
<td>Niérat, 1997</td>
<td>A service in which rail and truck services are combined to complete a door-to-door movement.</td>
</tr>
<tr>
<td>Harper &amp; Evers, 1993</td>
<td>One or more motor carriers provide the short-haul pick up and delivery service (drayage) segment of the trip and one or more railroads provide the long haul or line haul segment.</td>
</tr>
<tr>
<td>Evers, 1994</td>
<td>The movement of truck trailers/containers by both railroads and motor carriers during a single shipment.</td>
</tr>
<tr>
<td>Nozick &amp; Morlok, 1997</td>
<td>The movement of trucks and containers on railcars between terminals, with transport by truck at each end.</td>
</tr>
</tbody>
</table>

Table 2.1: Different authors and definitions of the term "Intermodal transport" [10]
Table 2.2: Modal split in the European Union [11]
has to be known. If the locations of traffics jams and the current location of the trucks in the fleet are also known real time calculations can be made to optimise the solution for the current situation. Figure 2.1b shows a possible solution of the problem in Figure 2.1a by letting the first truck drive along the green, and the second truck along the red route. This ensures all stores in the city are reached in the most fuel-efficient way.

2.1.2 Harbour

Since, as described in the last section, not all trucks can arrive on the same time, some containers need to be (temporary) stored in the harbour. This is done in the so called yard. Here rows of stacks of containers are stored waiting to be loaded onto a ship, barge, train or truck. When a truck enters with a container (or needs to be loaded with one) it will park next to a stack after which a gantry crane will move the container to (or from) the stack. Gantry cranes can either be fixed on a track or be a Rubber Tired Gantry crane (RTG). The main difference of course being the ability to move between stacks. For smaller stacks a special kind of RTG is used, called a straddle carrier. On the other side of the stacks the gantry crane nowadays often load the containers onto AGV’s which position the containers under the large ship-to-shore cranes. Especially large container vessels, also known as mega-containerships, can only dock at specific locations. To ensure shorter docking times, there is made use of so called feeder ships. Feeder ships transport containers from (or to) smaller harbours to (or from) the mega-containership. Most of the time the containers are not directly moved from the mega-containership to the feeder ships, but are temporary stored in the stacks. This is to prevent delays caused by differing arrival times between the ships, and to allow for reorganisation of the containers. [17]
2.1.3 Sea vessels

For sea-transport there is often made use of enormous ships, some of which can carry over 21000 TEU at a time [18]. Due to their size not many of these ships can dock at the same time. Docking time at seaports is expensive and divided into slots. Therefore it is important for the ships to arrive on time to prevent either extra charges for renting another timeslot and sometimes even more delays since the next slot is not always available. To prevent this the route and speed of the ship needs to be constantly updated taking account the weather and sea currents. This is especially important since due to the large inertia of the ship, changes take a lot of time to be made. For example: If a 50000t container ship cuts off its engines while going 15 m/s, it will take around 40 minutes and 11km to slow down to 2.5 m/s. [19]. The size of a ship is not only important for its inertia but also for its capability of taking certain routes. An example of this is the Panama Canal, which acts as a short-cut between the Pacific and the Atlantic ocean. In order to pass the canal ships initially had an allowable size of 294.13m maximum length, 32.31m maximum width and a maximum drought of 12.04m. The largest ships that comply to these demands are called Panamax ships. In 2014 however, new locks were completed allowing ships measuring 366m long by 49m wide and a draught of 15.2m to pass the canal. Where the ships made for passing the old locks were capable of transporting a maximum of 5000TEU, ships that are designed for the New Panamax class can transport 13000TEU. Other classes include the Suezmax, the maximum allowable size for the Suez-canal, and Q-max or Qatar-max, the largest size of ships that is able to dock in Qatar. [20]

2.1.4 Barges

For transport from the sea harbours to the hinterland there can be made use of barges. While barges move slower than container trucks, the amount of TEU’s they can transport at once makes up to the difference. Where most trucks can move one or two TEU’s a barge can move 32 up to 960 TEU’s at once [21]. This means that the amount of fuel per kilometre per TEU is lower than the container trucks. Another benefit of barges over trucks is traffic. While barges do encounter marine traffic and even may have to wait for bridges to open, real traffic jams, like on highways are extremely rare. A disadvantage is however the accessibility, since rivers and canals are not always available, and the fact that there are rarely alternative routes when the main route is unavailable (for example when a bridge breaks).

2.1.5 Train

While trains are less efficient than barges they have several advantages. One of these advantages is that the webbed nature of railway networks allows for rerouteing when necessary. Another very important advantage is that railways can be placed in almost every terrain, in contrast to barges which need an existing river, or expensive canals to move. For transport over great distances of land rail is therefore the best transport mode. This is the reason that the Chinese Belt and Road initiative, which created a cargo railway between China and Europe, was created. [22]. An important disadvantage in rail transport is where truck and barge transport have free movement and can swerve to avoid accidents, trains are fixed to their tracks. This, combined with the fact that, due to their large mass, trains take a lot of distance to come to a halt, means that accidents need to be prevented on another way. The most common way of accident prevention on trains is to divide the tracks into sections, in which only one train is allowed to be on a given time. By knowing is the upcoming section of rail is free or not a train operator can either continue or stop the train. The length of these section allows the train enough distance to safely come to a halt.

2.2 Tracking, tracing and monitoring

While route planning is an important interface between intermodal transport and satellite navigation, it is not the only one. Tracking tracing and monitoring all use satellite navigation and are a part of the intermodal transport processes that can not be ignored. Tracking and tracing are often used as one term, of which there is not one unified definition as noted by [12] which can be seen in table 2.3. [12] also adds a new definition to this list namely:

Tracking and tracing in the extensive sense encompasses tracking and tracing in the restricted sense. On-line information is not only used for cradle-to-grave tracking and tracing but is also used in the management and control of lots in successive stages of production. In
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>APICS Dictionary (1992)</td>
<td>A twofold view on traceability is put forward: traceability is (1) the attribute that allows the ongoing location of a shipment to be determined, and traceability is (2) the registering and tracking of parts, processes and materials used in production, by lot or serial number</td>
</tr>
<tr>
<td>Beulens et al. (1999)</td>
<td>Traceability is the ability to document the history of delivered goods and services and to prove conformance to specifications. Moreover, with respect to tracking and tracing it is indicated that long after closing a particular business transaction, the customer and supplier still are subject to a relationship</td>
</tr>
<tr>
<td>ISO (1994)</td>
<td>Traceability is the ability to trace the history, application or location of an entity by means of recorded identification. ISO relates traceability to the origin of materials and parts, the product processing history and the distribution and location of the product after delivery. According to ISO, traceability includes the set of interrelated resources and activities which transform inputs into outputs</td>
</tr>
<tr>
<td>Jansen (1998)</td>
<td>A distinction exists between product tracking and product tracing. Product tracking originates from product value or risk, whereby one wishes to locate the products. Product tracing originates from exception handling, whereby one wishes to establish the source of (bad) quality</td>
</tr>
<tr>
<td>Kim et al. (1995)</td>
<td>Traceability is referred to as clear knowledge of ancestry whereby the entities to trace (in this reference, ISO 9000 products and activities); depend on unique identification; traceability relations are commented on by a graphical notation of ancestry</td>
</tr>
<tr>
<td>MESA (1997)</td>
<td>Traceability comes down to product tracking and genealogy, it provides the visibility to where work is at all times and its disposition. Status information can include who is working on it, components, materials, batch, supplier, lot, serial number, current production conditions, any alarms, rework or exceptions related to products. Besides visibility, an on-line tracking function creates a historic record, allowing the traceability of components and usage of each end product</td>
</tr>
<tr>
<td>Moe (1998)</td>
<td>Traceability is viewed as an ability by which one may track a product batch and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales (read: “chain traceability”), or internally in one of the steps in the chain, for example the production step (read: “internal traceability”)</td>
</tr>
<tr>
<td>Rijn et al. (1993)</td>
<td>Traceability relates to WIP (work in progress), defining it as the identification of a lot or batch of material, the tracking information (location and quality), and the tracing information (where from and where used) of material</td>
</tr>
<tr>
<td>van Twillert (1999)</td>
<td>Tracking and tracing may be subdivided into a tracking part and a forward and backward traceability part. The tracking part consists of the determination of the ongoing location of items during their way through the supply chain. The forward traceability part refers to the determination of the location of items in the supply chain which were produced together using, for example, a contamination of the history of a certain item. Backward tracing is used to determine the source of the problem of a defective item</td>
</tr>
<tr>
<td>Weigand (1997)</td>
<td>Tracking and tracing is considered a modern tool that gives insight into the origin of products to all links of the supply chain, insight which is used to optimise the processes in the separate links and to enhance the total supply chain</td>
</tr>
<tr>
<td>Wilson and Clarke (1998)</td>
<td>Food traceability can be defined as the kind of information necessary to describe the production history of a food crop and any subsequent transformations or processes that the crop might be subject to on its journey from the grower to the consumer plate</td>
</tr>
</tbody>
</table>

Table 2.3: Different authors and definitions of the term "tracking and tracing" [12]
this respect, information on lot properties provides for the possibility of dynamic lot allocation in order to obviate quality variation during production. Tracking and tracing in such extensive sense refers to the optimisation and control of processes in and between separate links of the supply chain, for which the on-line tracking of lots and storage of data on lot properties is indispensable.

There is also an argument that tracking and tracing should be viewed as two separate terms: tracking for keeping track of the location during a transport process, and tracing for keeping track of the source of the cargo (mainly for quality control) [23, 24]. Most definitions agree that the tracing and tracking of goods includes having information sent at several checkpoints. This information includes the location of the checkpoint the identifying information of the cargo and the time that the cargo arrived at the checkpoint [25]. In a transport process this information is often relayed to the customer to give an estimation of how far along the transport the cargo is and when it will arrive on the destination. The first of these systems used check-list to determine what cargo was at what checkpoint. Later these check-lists are mostly replaced by barcodes, QR-codes and RFID tags for automated scanning at checkpoints. Newer systems use GPS-trackers in vehicle to make a so called moving checkpoint or use GPS-trackers in the cargo for realtime tracking. Monitoring the cargo is mainly to prevent loss by theft. Monitoring can be divided in to two categories: passive monitoring and active monitoring. Passive monitoring includes the previous mentioned barcodes, QR-codes and RFID tags to ensure cargo was not switched out, and safety seals to prevent tempering. These methods have to be (manually) checked, where active systems give transmit their status automatically.

Active monitoring is the use of covert electronic tracking devices placed within the cargo and monitored remotely by an internal, or contracted, control centre. This process provides a method of checking the location of loads at predetermined intervals (e.g., every 15 minutes, 30 minutes, hour) and also monitors the compliance of in-transit security requirements, such as stopping only in authorized areas, on-time delivery, and loads remaining on the pre approved route. [26]
Chapter 3

Satellite navigation systems

While it is common to use the term Global Positioning System (GPS) for all satellite navigation, it is actually but one of many different systems. In this literature study the most important global systems will be discussed in section 3.2. While each of this systems is different from the others the main working principle is identical as discussed in section 3.1.

3.1 Working principles

3.1.1 Doppler-based satellite systems

As described by [3], the first satellite navigation and location systems worked by making use of the Doppler-effect. The main part of this system consists of satellites sending a constant frequency pulse, with a amplitude modulation carrying the orbit of the satellite and the time. By determining the Doppler shift a receiver can measure the movement of the satellite in regard to the receiver. This combined with the know orbit of the satellite enable the receiver to determine its location. To ensure correct measurements the satellites are regularly recalibrated by having the satellite fly by four known tracking stations, which measure the movement of the satellite and upload a recalibrated orbit prediction to the satellite. [3] Figure 3.1 gives a quick overview of this method. The downside to this system is that it is only accurate within a couple of hundreds of meters [27]. This lack of accuracy has resulted in the fact the Doppler systems are hardly ever used any more and are replaced by Time-based systems.

![Figure 3.1: an overview of a Doppler-based satellite system [3]](image-url)
3.1.2 Time-based systems

Newer systems like GPS and GLONASS do not make use of the Doppler effect. Instead, these systems determine the distance from the satellite to the receiver by comparing the time-of-flight of the signal send by the satellite. To calculate this time-of-flight the exact time, kept by an atomic clock on board, is included in the satellite location transmission. The receiver can then compare the different send times of different satellites to determine the time-of-flight, and thus the distance, of each signal. This information combined with the location information send by the satellites enable a modern receiver to triangulate its position within an 95%-accuracy of 3m horizontally and 5m vertically [28].

3.2 Types of systems

3.2.1 GPS

Global Positioning System or GPS is the most commonly known satellite navigation system. This system developed originally for the United States’ Military. It was declassified in 1983 by president Ronald Reagan, after a Korean civilian aircraft flew into prohibited airspace and was shot down by soviet fighters [29]. GPS currently uses 31 operational satellites flying at approximately 20,200 km. At least 95% of the time 24 of these satellites are operational. These 24 satellites are positioned in six orbits with each 4 slots. This is done to ensure that each point on earth is in range of at least four satellites. The accuracy of GPS is 5 meters. [30]

3.2.2 GLONASS

Globalnaya Navigatsionnaya Sputnikovaya Sistema or GLONASS is the Russian counterpart of GPS. The original concept was created in 1979 in the soviet era. The system was designed for 24 satellites in three orbits with each eight slots at 19,100 km[31]. However there were only twelve satellites launched before the soviet union dissolved. In 2001 president Vladimir Putin reinvested in the program [32]. The accuracy of GLONASS is 2.8 meters.[33] To promote the system in Russia a import tax on all GPS receivers was created, and a total ban on GPS systems unable to use GLONASS was proposed. However in 2004 an agreement was made between the United States of America and Russia to ensure interoperability between GPS and GLONASS. To achieve this GLONASS satellites now send an extra, GPS compatible, signal. [34]

3.2.3 BeiDou

BeiDou is the Chinese satellite navigation system. Started in the 1990s it consists of three phases. The first phase, BeiDou-1, consisted of only three satellites and was mainly for demonstrating and training purposes. The second phase, BeiDou-2, was a working regional satellite system which used 14 satellites and lasted till 2012. The final phase, BeiDou-3, is to create a global navigation network of 35 satellites. This network will have a location accuracy of 10m and a velocity accuracy of 0.2m/s\(^1\). The final phase should be completed in 2020.[35]

3.2.4 Galileo

Since 1999 the European union is building its own satellite navigation system named after famous astrologer Galileo Galilei. Just as GLONASS and BeiDou it was made to be less dependent on the American GPS. To increase the adaptation to Galileo, the system was designed to be compatible with GPS signals. The constellation consist of 30 satellites orbiting at roughly 23000km. While the system does currently not provide full global coverage, it is planned to do so in 2020. Theoretically the system could provide an accuracy of 30cm, but in reality this will be closer to 1 meter. [36] [37]

\(^1\)These accuracies are the civilian accuracies, military accuracies will most likely be even more precise.
### Table 3.1: An overview of the different systems and their properties

<table>
<thead>
<tr>
<th>System</th>
<th>Amount of Satellites</th>
<th>Accuracy</th>
<th>Global coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Positioning System (GPS)</td>
<td>24 (33)</td>
<td>5 meters</td>
<td>Yes</td>
</tr>
<tr>
<td>Globalnaya navigatsionnaya sputnikovaya sistema (GLONASS)</td>
<td>24 (27)</td>
<td>2.8 meters</td>
<td>Yes</td>
</tr>
<tr>
<td>BeiDou</td>
<td>35 (30)</td>
<td>10 meters</td>
<td>expected in 2020</td>
</tr>
<tr>
<td>Galileo</td>
<td>24 (30)</td>
<td>1 meter</td>
<td>expected in 2020</td>
</tr>
</tbody>
</table>

### 3.3 Comparison between systems

While the goal of all these satellite navigation systems is the same, and even tough most modern navigations systems are compatible with multiple or even all of these systems, there are still some differences. Some examples of this can be seen in Table 3.1. In the next part some of the differences will be explained.

#### 3.3.1 Amount of satellites

While each of the systems in 3.2 aims for global coverage, the amount of satellites that are used to achieve this goals differ. In order to have global coverage, GPS needs 24 working satellites at all times. Therefore the goal is set to have 95% of the time at least 24 working satellites in orbit. To do this the target is to launch an additional nine satellites as back-ups and to replace decommissioned satellites, bringing the total number of satellites to 33. GLONASS is set up to need 18 satellites for coverage of Russia and 24 for global coverage. These satellites are divided in three orbits of nine satellites, providing each orbit an backup satellite and bringing to total to 27. Beidou uses the most satellites with 35, but five of these are only used for backwards compatibility with BeiDou-1. Galileo uses 24 satellites in three planes of eight with two spare satellites per plane resulting in a total of 30 satellites.

#### 3.3.2 Accuracy

While each system reports a different accuracy, as can be seen in Table 3.1, this accuracy is not the real accuracy that can be achieved. Part of this is due to the fact that consumer devices do not have access to the complete signal, since this is partly encoded for military purposes. But even the signal that is open for consumer use is in theory more accurate than in practice is achieved. The greatest decrease in accuracy is that due to obstructions the signal is weakened, decreasing the amount of available satellites for the receiver. In urban environments this is can be caused by buildings obstructing and reflecting signals. This can result in the fact that a directed signal form a satellite is blocked, while a reflected signal, which has a longer time-of-flight, is received, as can be seen in Figure 3.2. This will cause the triangulation algorithm to calculate a wrong location. In a world-wide experiments using GPS it was found that the effect of this increases with the height of the buildings in what is called the Law of Urban Multipath, see Equation 3.1. [38]

\[
\text{meanaccuracy}(m) = \text{buildingheight}(\text{floors}) + 5(m) \quad (3.1)
\]

While the reflection and obstruction by buildings is diminishing the signal, cities also have a lot of electromagnetic noise. This noise is partly caused by devices transmitting on the same frequency bands as the satellite and partly by poorly insulated devices emitting broad-band noise. [39] Another important influence on the accuracy of satellite navigation is the iono- and troposphere of the earth, where charged particles can interfere with the signal. Less often the signal is disrupted by solar flares, carrying enormous amounts of charged particles.

To improve accuracy ground based systems such as (Nationwide) Differential GPS or (N)DGPS can be used. DGPS is an enhanced version of GPS that makes use of fixed ground transmitters. These stationary antennas receive GPS information over a relative long time span, allowing for error calculation. When
these calculations are done a correcting signal is send to reduce the error in nearby receivers as can be seen in Figure 3.3. This Figure shows a reference station, which processes the signal from multiple GPS satellites and calculates corrections. These corrections are broadcast by an antenna and received alongside the original GPS signal by the mobile stations such as cars, airplanes, and ships. These mobile stations use the correction signal to adjust their calculations and to determine their location more accurate. [4]

3.3.3 Global coverage

Since GPS and GLONASS are older than their Chinese and European counterparts, they have had more time to achieve full coverage. The two newer systems have not, but both systems are expected to have full coverage in 2020. This can be noticed from the flight pattern of the available satellites as shown in Figure 3.4.

Figure 3.4 also shows clearly that BeiDou started as a regional network over China, where full coverage is achieved. Other parts of the world have almost no coverage. This is in contrast with Galileo which is designed as a global network and has a more spread out coverage.
Figure 3.4: Ground tracks of four-satellite navigation systems as of September 2013: BeiDou, Galileo, GLONASS and GPS, from top to down; the different colors and times are selected only for better distinction and display of trajectories [5]
Chapter 4

Applications

All of the modes in chapter 2 can and make use of satellite navigation in their own way. In this chapter an overview of the existing systems is given for each of these transport modes.

4.1 Truck

4.1.1 Current applications

There are many available GPS-systems designed for trucks. These include hand-held devices as the TomTom Trucker 520, and the Garmin dezl™770LMTHD [40][41]. But there are also apps available like TruckerPath that use the GPS build in a phone to navigate [42]. These systems take into account the weight and height of the truck preventing routes that go over weak bridges and small tunnels. [43] Just as consumer GPS-systems these systems also account for traffic and roadwork, recalculating the route when changes occur. To calculate the route navigation systems make use of regular traffic patterns, such as high demand during rush hours and low demand during nights, in combination with the demand of the lasts fifteen minutes. This way both the regular demand and the irregular demand due to roadwork or accidents is accounted for. [44][45] While there are similar navigation systems available for the Beidou system, no truck navigation for GLONASS and Galileo could be found.

4.1.2 Future applications

The most prominent upcoming technology in container transport via trucks is the introduction of autonomous trucks. These trucks are currently in development all over the world and should drive more effective than human controlled trucks. The main improvement shall be in the interaction with other traffic by reducing stop-and-go traffic waves. [46] While (most) navigation systems in human controlled trucks can adapt their route in real-time, autonomous trucks go one step further. By communicating the position speed and current route to each other the autonomous trucks can adapt their routes, creating an optimal route for all trucks in the area, reducing traffic jams. [47]. While this technology looks very promising there are some issues that have to be worked at before it can be implemented on a larger scale. The main issue is not in the technology itself but in the legal part: When an accident occurs involving a autonomous truck, who is responsible: the owner, the manufacturer or the designer?

4.2 Harbour

4.2.1 Current applications

There are multiple uses for satellite navigation within a harbour. The first one is to regulate the traffic of the seavessels, barges and tugboats, in such a way that each of these gets at their desired position in time. The second use is in the AGV’s. These vehicles need to know not only their own exact position, but also that of the other AGV’s in their area. While the AGV’s are equipped with sensors to prevent collisions, the main part of collision prevention lies in the route planning mainframe which locates and coordinates all the AGV’s. This is possible because there are no other vehicles (or people) allowed in the working space of the AGV’s. Furthermore to reduce measurement errors, there are placed multiple DGPS stations in the harbour. these fixed ground stations will send a secondary signal to correct the
position. This makes it possible to know not only the position of the AGV’s but also that of every container and straddle carrier in the yard. [48] Another, less known usage of satellite navigation systems is to measure the tides. Since especially large ships cannot enter or leave the harbour on low water, it is vital to know the tides and to be able to predict them (to some extent). To do an antenna on the shore measures the time (and thus distance) difference between direct GPS signals and signals that have been reflected by the waves. [49]

4.2.2 Future applications

While the transport processes, and therefore the harbours, are ever changing, there are few changes regarding the use of satellite navigation. This is mainly because of the static nature of the large equipment, such as the ship-to-shore cranes and the gantry cranes which do not need to use satellite navigation, and the advanced state of development in the smaller equipment like the AGV’s, which are already fully using satellite navigation.

4.3 Seavessels

4.3.1 Current applications

For centuries navigation on sea was done by using celestial navigation. While this is reasonably accurate, this can only be done when at least two celestial body are visible. This means that on cloudy days there was no navigation possible expect for keeping a direction using a compass. The result of this was that most ships did arrive at their destination, but not at the most efficient route. For example: The route between Troy and Ithaca should take around 4 days in a Trireme, but due to inefficient navigation (and some personal problems between a captain and some gods) this could take up to ten years [50]. Satellite navigation systems are not hindered by clouds, and provide a significantly better accuracy, and was therefore quickly embraced by seafarers worldwide. The better accuracy combined with satellite imaging make accounting for sea currents and weather easier and allows for constantly optimised routes. [51] Due to their enormous mass, one would expect seavessels to have a large draft. However due to their design the draft of most container vessels is relatively small, as can be seen in Figure 4.1. This draft will cause no problems on most of the oceans, since the average depths are more than tenfold the draft of these ships as can be seen in Table 4.1. Near the coast waters are less deep, creating, especially considering the influence of the tide and the weather, the danger of running the vessel aground. To prevent this it is vital to known the current depth of the water. This can be done by using sonar on board of the vessels,
Table 4.1: Volumes of the World’s Oceans from ETOPO1 [13]

<table>
<thead>
<tr>
<th>Ocean</th>
<th>Area (km²)</th>
<th>% Ocean Area</th>
<th>Volume (m³)</th>
<th>% Ocean Volume</th>
<th>Avg. Depth (m)</th>
<th>Max Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Ocean</td>
<td>15,568,000</td>
<td>43</td>
<td>10,750,000</td>
<td>23.5</td>
<td>1205</td>
<td>5587</td>
</tr>
<tr>
<td>Atlantic Ocean</td>
<td>86,130,000</td>
<td>23.5</td>
<td>510,410,900</td>
<td>23.5</td>
<td>3646</td>
<td>8486</td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>406,000</td>
<td>0.1</td>
<td>20,900</td>
<td>0.0</td>
<td>51</td>
<td>392</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>2,977,000</td>
<td>0.8</td>
<td>4,930,000</td>
<td>0.3</td>
<td>1450</td>
<td>5139</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>41,460,000</td>
<td>11.5</td>
<td>146,000,000</td>
<td>10.9</td>
<td>3519</td>
<td>8486</td>
</tr>
<tr>
<td>South Atlantic</td>
<td>40,270,000</td>
<td>11.1</td>
<td>160,000,000</td>
<td>12.0</td>
<td>3973</td>
<td>6240</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>70,560,000</td>
<td>19.5</td>
<td>294,000,000</td>
<td>19.8</td>
<td>3741</td>
<td>7906</td>
</tr>
<tr>
<td>Pacific Ocean</td>
<td>161,760,000</td>
<td>44.7</td>
<td>660,000,000</td>
<td>49.4</td>
<td>4080</td>
<td>10,803</td>
</tr>
<tr>
<td>North Pacific</td>
<td>77,010,000</td>
<td>21.3</td>
<td>331,000,000</td>
<td>24.8</td>
<td>4298</td>
<td>10,803</td>
</tr>
<tr>
<td>South Pacific</td>
<td>84,750,000</td>
<td>23.4</td>
<td>309,000,000</td>
<td>24.6</td>
<td>3882</td>
<td>10,753</td>
</tr>
<tr>
<td>China Sea</td>
<td>8,983,000</td>
<td>1.9</td>
<td>8,890,000</td>
<td>0.7</td>
<td>1419</td>
<td>7352</td>
</tr>
<tr>
<td>Southern Ocean</td>
<td>21,960,000</td>
<td>6.1</td>
<td>71,800,000</td>
<td>5.4</td>
<td>3270</td>
<td>7075</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>361,900,000</strong></td>
<td><strong>100.0</strong></td>
<td><strong>1,335,000,000</strong></td>
<td><strong>100.0</strong></td>
<td><strong>3688</strong></td>
<td><strong>10,803</strong></td>
</tr>
</tbody>
</table>

* Errors: 0.1% ** Total surface area of Earth is 510,072,000 sq. km. The oceans cover ~70.9%.
* Southern Ocean area and volume calculated from ETOPO1 Bafetik version (includes Waddell and Ross seas without ice cover).
* Deepest ocean depth is in the Marianas Trench, measured at 11,911 meters. Maximum depths from ETOPO1 are not expected to exactly match known measured maximum depths as ETOPO1 represents average depths over ~4 sq. km areas.

and by having surveying ships measure the depth compared to average sea level and charting them for use in satellite navigation. While this second method is useful for the overall shape of the ocean floor due to the inaccuracies of the satellite navigation, this is only accurate to several decimetres. This can be seen in Figure 4.2. The exact height needs to be always monitored by the vessel itself, since ocean currents can create new sandbanks that are not yet charted. Due to the large mass of the vessels, once a small under keel clearance (UKC) is measured, it takes a lot of to change course. This large reaction time means that large margin have to be taken into account to prevent accidents. [7]

4.3.2 Future applications

In the future survey ship can accurately measure and chart the depth of the sea bedding, combined with a calculated tide reference ellipsoid the margins for UKC can be greatly reduced. This is done by combining a more accurate vertical satellite calculation with an so called geodetic datum: an height calculation based of the earth’s gravity. the result of this can be seen in Figure 4.3. [7] Just as trucks sea vessels can be operated more effectively when not controlled by a human but by a computer. This is why, as trucks, the sea vessels shall make the switch from human operated to computer operated. The difference here is that, while there is some traffic to account for, the routes of sea vessels are mainly dictated by the weather and currents. Since these factors, while ever changing, are easier to predict than human behaviour, the development of sea vessels is quicker then that of trucks, with a planned launch of an autonomous ship in 2020. [52]

4.4 Barges

4.4.1 Current applications

Barges often have no alternative routes, as described in section 2.1.4, so rerouteing using satellite navigation is not an option. Satellite navigation is used however in the Automatic Identification System (AIS), which communicates the position, velocity and direction of the barge to other traffic, preventing collisions.[53][54] Another use of AIS is at locks, where ships can announce their arrival ahead of time and get a place in a virtual queue, as can be seen in Figure 4.4. By knowing the exact time the barge can pass through the lock, it can adjust its speed to match its arrival time. This conserves fuel and reduced environmental impact. [55] [8]
Figure 4.2: The present chart datum (Mean Sea Level in the Baltic Sea) includes relatively large uncertainties. Therefore conservatively applying large Under Keel Clearance margins is vital for safe vessel navigation. [7]

Figure 4.3: With an accurate geodetic chart datum it is straight-forward to calculate Under Keel Clearance from a height measurement obtained by the vessel’s satellite positioning system. This gives the navigator much better control of the actual UKC of the vessel. [7]
4.4.2 Future applications

Since barges have no alternative routes, the automation mainly focuses on maintaining the correct speed for arriving at bridges and locks. Knowing the current speed and velocity is done by GPS, and vitally important because of the large inertia of the ships, and little to no space for evasive actions. Where autonomous trucks have to take into account the traffic around them, this is less important for autonomous barges since they have, due to their size, almost always right of way. This results in the fact that designing autonomous barges is a simpler task than either trucks or sea vessels and that the first autonomous barges are expected in August of 2018. [56]

4.5 Train

4.5.1 Current applications

As described in section 2.1.5, it is vitally important for trains to know what the status is of the next section of track. To do this various systems can be used, one of which is the European Train Control System, ETCS. ETCS is designed as part of the European Rail Traffic Management System (ERTMS) not only to prevent accidents but also to unify safety systems across Europe. This is important because there are currently over twenty different safety systems, forcing either for cargo to switch trains at borders or trains (and personnel) to be compatible with multiple systems. Not only does this cost a lot of money, the greater complexity results in a greater chance of failures. Also, since most of the current systems are dated a new (unified) system could improve the capacity of the existing rail network by 40%. [57] The system will be implemented in three phases, each more advanced but compatible with its predecessor. The first system uses so called eurobalises to determine the location of the trains and existing lineside signals to inform the driver if it is safe to continue. If the speed of the train exceeds the set speed-limit the train will automatically brake. This is combined with a so called track-circuit which determines train integrity to ensure no carts have broken off the train. This results in a situation as can be seen in Figure 4.5. The second level does not use lineside signals but a radio signal between the train and a radio block centre to give (or deny) permission to continue. This changes to information stream to the driver from intermittent (lineside signals) to a continues signal (an on-board display). This allows for an increase in train-speed, which was previously limited by drivers being able to accurately read the lineside signals. Figure 4.6 shows an overview of this level. The final system uses a combination of eurobalises and virtual eurobalises by use of GPS. These are used to determine the exact location and velocity of a train, which is
Figure 4.5: A level 1 ETCS system [9]

Figure 4.6: A level 2 ETCS system [9]
communicated to central control stations. These stations can use this information to set the availability of track sections, which is communicated back to the trains and used to adjust velocity where needed. The track-circuits are replaced by an on-board integrity check. The result of this can be seen in Figure 4.7 [9]

4.5.2 Future applications
In the future ETCS will be adapted in it’s final level all over Europe allowing for so called moving block system, increasing the capacity of the rails and eliminating the need for on-board drivers. This system will depend on control rooms, rooms where a human supervisor can oversee multiple semi-autonomous trains in the area at the same time. To do this is is vitally important that the exact location of these trains is known. This is why not only satellite navigation shall be used, but also the aforementioned eurobalises shall be used for error reduction. When a train arrives at a border crossing there will not only be contact between the train and the control rooms of the two areas but also between the two control rooms themselves to ensure a safe transition.

4.6 Other technologies

4.6.1 Current applications
Shipping companies often offer a tracking service, letting the customer know where their cargo is and when they can expect it to be delivered. Aside from the convenience of knowing the delivery date (and time), this also helps recovering lost cargo, by starting the search at the last tracked location. Most tracking services work by having (bar)codes scanned at transport nodes such as airports and harbours, but some services use satellite trackers in the containers for real-time tracking. This last method prevents lost cargo almost entirely since the exact location is always known.

4.6.2 Future applications
what other technologies and applications may be developed in the future is unknown. This is mostly because when a completely new technology is developed, the company that is developing it often keeps this a secret until a product featuring the new technology is ready for sale, to prevent competition form outpacing them in their own technology.
Chapter 5

Conclusion

This study looked at intermodal transport and the applications of satellite navigation. As shown, satellite navigation already has a great number of applications within the transport, varying from the positioning of AGV’s, to preventing traffic jams, to measuring the tides. It can be concluded that where satellite navigation is now used to provide people with information to use to control vehicles, this will soon be handled directly by computers as is already done with the AGV’s in the harbour. While most of this technology is ready to go, the main hold up is the legal part, since there are no clear laws governing autonomous vehicles yet. Other techniques such as measuring the water level and real-time tracking of individual containers will undergo fewer changes. To clarify those changes one can look at the total transport of a container.

Nowadays a container may be picked up at a distribution centre by a container truck, which uses a GPS navigation device to direct its driver to an inland harbour. Here the container will be placed on a barge to bring the container to the sea port. To prevent unnecessary braking of the barge, the barges uses its satellite navigation system to transmit its location and heading to bridges and locks on its way to the port. In this port a straddle carrier will pick up the container and place it on an AGV, which uses a satellite navigation system as a direct input of it’s control software. A ship-to-shore crane will place the container from the AGV onto a sea vessel, which uses satellite navigation to determine its course to the next harbour. In the next harbour a satellite based tide sensor determines if the sea vessel can enter, after which to container is placed on a train which is kept safe by ERMTS, using it’s on board satellite navigation system. The Train delivers the container to it’s destination: a distribution station where the customer is already waiting, knowing the exact location (and thus arrival time) of the container by using the GPS tracker inside.

In the future the container may be picked up by a self driving truck, placed onto an autonomous barge and in the port transferred to an autonomous sea-vessel. Upon arriving in the next port the container can be placed on a train which is not directly controlled by an engineer, but alongside several trains from within a control station.
Bibliography


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