PRT Vehicle Architecture and Control in Masdar City

Menno de Graaf

Product Development, Cargotec ACT, Proostwetering 26, 3543 AE Utrecht, The Netherlands; phone +31 30 241 54 22; menno@advancedcargo.eu

Abstract

The carbon neutral, zero emission Masdar city incorporates Personal Rapid Transit (PRT), the solution that provides on-demand, private transit directly from origin to destination. The city will feature a network of guide-ways with a large station density ensuring short walking distances (maximum 150 meters). The guide-ways are located at grade, while the pedestrian level is elevated to create a new street level (the podium).

In the first phase of the network, operations will start with 10 PRT vehicles sharing the track with 3 freight (FRT) vehicles. A total number of 6 stations are available: 2 people stations, 3 freight stations and a maintenance station.

The paper addresses the technical side of the PRT operation. The vehicle architecture is presented, including an overview of the important vehicle components with their purpose. The main working principles of the vehicle control system, used to guide the vehicles accurately along the track, are discussed. Results of the actual driving performance and accuracy are incorporated to show that the vehicle control system is well capable of meeting the high demands of driverless people transit.

Introduction

Personal Rapid Transit (PRT) is an automated taxi-like service concept, which combines the characteristics of the personal automobile, the advantages of public transportation (congestion, parking) and clean technologies and is therefore the ideal transit system in the carbon neutral, zero emission Masdar city.

System overview

Although this paper focuses on the vehicles, some words will be spent on the system as a whole, to get a good understanding of the context in which the vehicles are operating and how they interact and communicate with their surroundings.

A major role in the system is played by the supervisory control system TOMS (Transit and Operation Monitoring Software). Its task is to monitor and control the system as a whole, by keeping the status of the system, taking care of traffic rules, distributing route segments to the vehicles, etc. TOMS communicates with the other system components through a wired network and with the vehicles through a wireless network.

The system operator uses the TOMS GUI to operate the system from the control room. From the GUI he can visualize the status of the vehicles on the track, monitor the operation and give manual movement or charge orders if desired. In the control room the images of different camera's in the vehicles and at the stations can be seen and replayed to observe what happened some time ago. Also, an intercom is present to let the operator speak with people in a specific vehicles, or send broadcast messages to all vehicles at the same time.

In every station, a station controller is present. Its task is to monitor the status of station doors, charge pads and/or roller shutter doors (for FRT stations). It takes care of opening the station doors (synchronously with the vehicle doors), connecting the charge pads to the vehicle, etc.

From a passengers point of view, the stations are equipped with station GUIs that show which vehicles are ready for operation (some may be busy charging). When someone enters the vehicle, an instruction audio message is played to take a seat and start the trip by pressing a button on the vehicle touch screen. When the start button is pressed, the TOMS server will be notified, which in turn computes the optimal route to the destination, sends route segments to the vehicle until the passenger has reached its destination. During the trip, information like the remaining trip time will be shown on the vehicle touch screen.

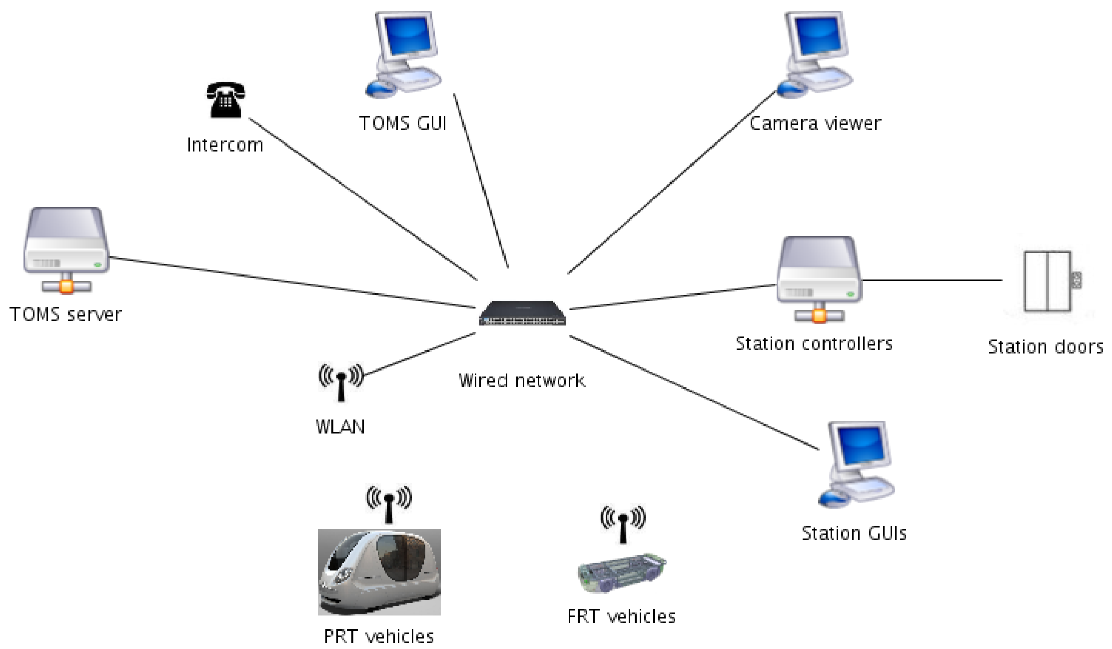

Figure 1 - System architecture

Track layout

In the first phase of the network, operations will start with 10 PRT vehicles sharing the track with 3 freight vehicles. A total number of 6 stations are available: 2 people stations, 3 freight stations and a maintenance station.

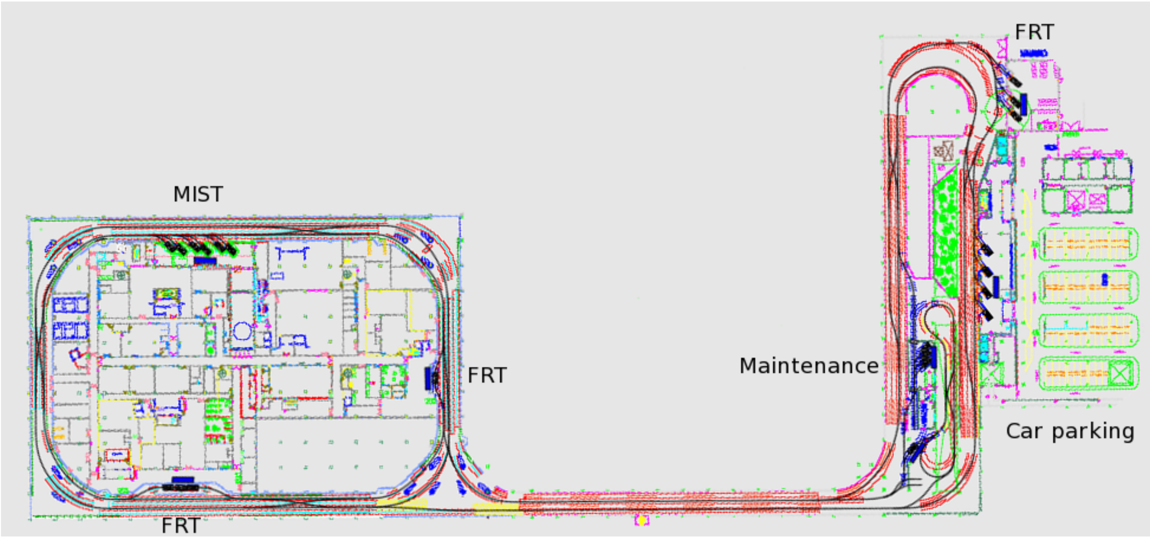

Figure 2 - Track layout

People who are visiting the Masdar Institute of Science and Technology (MIST) can park their car at the car parking facility and enter one of the PRT vehicles at the station, which will bring them to station MIST.

Vehicle Overview

The vehicles main energy source is a $FePO_4$ Li-ion battery. Main advantages are a high cycle time, it is environment friendly, has a good power weight density and a very good thermal performance. The battery provides power to the different vehicle components. An onboard battery management system keeps track of the battery voltage and state of charge. In combination with an on onboard charger this makes sure the different battery cells are equally charged.

Vehicles are equipped with air conditioning, which is a necessity in the hot desert climate. The air conditioning system can operate in two modes: normal and boost mode. The airco boost mode provides extra cooling power and is used at the stations when the vehicles are connected to a charge pad. During the trip, the normal mode prevents the vehicle from heating up. As the air conditioning system is a major power drain for the battery, using these airco modes a good trade off between driving distance and driving comfort was obtained.

Passengers can enter the vehicle by pressing the door touch button. A door controller takes care of synchronous opening and closing of the two doors, but only when this is allowed, e.g. the doors may only be operated at the stations, never when the vehicle is driving. Also when a vehicle is waiting in between the stations, no door operation is allowed to prevent people from entering the track and thus disturbing the operation. A manual override button is present, to allow passengers to open the doors and leave the vehicle in case of an emergency. When this button is pressed, operators will be informed and TOMS will be notified and freezes the area around the vehicle to prevent other vehicles from entering and leaving this area.

The PRT vehicles are equipped with a graphical touch screen, from which the passenger can start the trip. During driving it shows information like remaining time to destination. Passengers are informed with audio messages (english and arabic) how to use the system and when exceptions occur (door blocked, vehicle failure, waiting for zone, etc). If additional information is needed, the system operator can be called with the intercom.

Figure 3 - PRT vehicle

Vehicle Architecture

Both the PRT and FRT vehicles are built upon the same chassis. Therefore from a control point of view, these types of vehicles behave in a similar way (although the mass is different and the FRT vehicles have a larger drive motor).

This section discusses the vehicle architecture, i.e. the guidance components that are needed to guide a vehicle automatically along the track. These components are present in both PRT and FRT vehicles and can be divided in sensors (needed to determine an estimate of the vehicle position) and actuators (needed to move the vehicle close to the desired route with the desired speed).

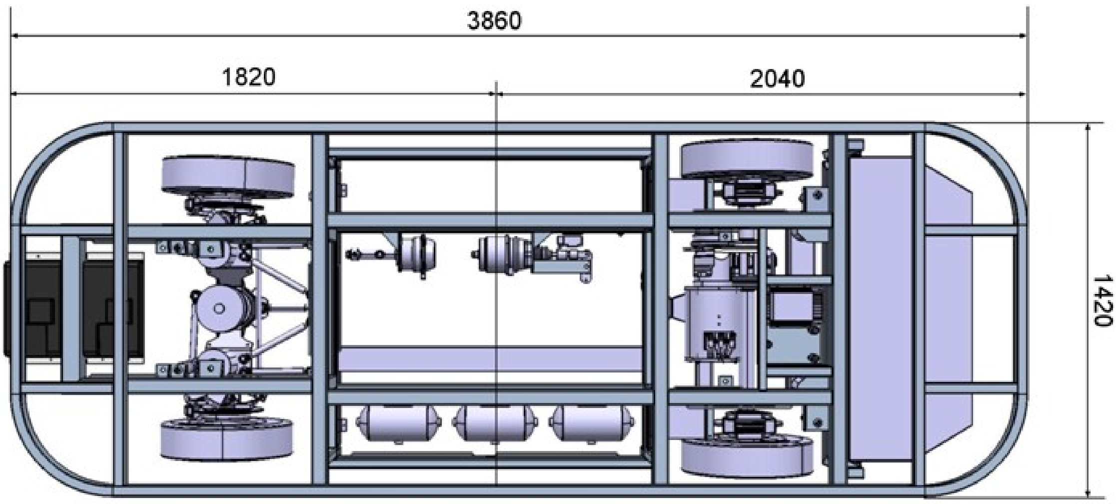

Figure 4 - Vehicle chassis

Vehicle Control Computer

The vehicle control software is running on a dedicated industrial computer and this combination forms the heart (or brains) of the system as all the computations are done here. The vehicle control computer (VCC) is in principle a general purpose computer, although it has some features that are particular useful for this application: it contains no moving parts, uses 24V supply, has a high temperature range and has integrated CAN hardware to communicate with the other vehicle components.

The VCC has a linux-based operating system with real-time kernel extensions to achieve better guarantees that computation tasks are handled in a predictable way.

Wheel encoders

All four wheels have integrated wheel encoders, which are the main sensors for determining the vehicle motion (in combination with the known wheel diameter). As the wheel encoders form a redundant set, both the safety and reliability of the system increases, i.e. there is still enough information present to determine a valid motion estimate if some of the wheel encoders are not giving correct information, which can be caused by hardware malfunctioning or wheel slip during heavy braking.

Steer encoders

Steer encoders are mounted on the fusee axes of both steering wheels. They measure the rotation angle of the steering wheels. Again, a redundant set is available as the left and right fusee axis are linked by the steering rod system and therefore the relation between the two is fixed.

Gyroscope

The gyroscope measures the rotation of the vehicle and plays an important role in determining an accurate estimate of the rotation of the vehicle, which is especially important when driving through corners. Although the rotation of the vehicle can also be determined from the wheel and steer encoders alone, the accuracy is greatly increased with the use of the gyroscope as it measures vehicle rotation independently of wheel slip effects.

The wheel encoders, steer encoders and gyroscope form again a redundant set of measurements, which is used to get rid of the drift effect that is present in gyroscopes, e.g. even though a gyroscope is held perfectly still, it will still give some rotation over time.

Magnet measurement system

The magnet measurement system measures the relative position of magnets that are drilled in the floor. Using a model of the magnet field, the measurement data is processed and the magnet position is determined. Based on the deviation between measurements and model, incorrect measurements are detected and discarded (all done in the magnet measurement system). The magnet measurement system is validated to give accurate results with speeds over 80 km/hr and can be used up to 30cm above floor level.

Steer system

The vehicles are using front wheel steering. A steer servo is connected to the steer motor. Through a reduction, it is connected to the steer rod system, which is responsible for accurate tracking of the steering wheels in corners.

Drive system

The vehicles are using rear wheel driving. A drive servo delivers power to the drive motor, which is connected to the rear axis through a differential. The drive system is capable of regenerative braking in which case energy is stored back into the main battery.

Brake system

There are two separate brake systems: a fail safe parking brake, which is connected to the differential and needs to be actively lifted, and a proportional brake system, which applies brake force to all four wheels. The amount of proportional brake force can be controlled from the VCS, while the fail safe parking brake is just a switchable brake. The latter is connected to the emergency circuit, so in case the circuit is down, the vehicle will come to standstill.

Obstacle detection system

Although the area in which the vehicles are driving is supposed to be free from obstacles, obstacle detection is present on the vehicles, which prevents collisions to other vehicles, passengers, animals and objects that may be present in exceptional situations.

Ultrasonic sensors are mounted in the rear bumper and provide short range detection (up to 2.5 m). An automotive laser scanner is located in the front of the vehicle and gives a long range detection (up to 60m), which is obviously needed when driving at high speeds.

The obstacle detection system scans the path the vehicle has to drive for objects and has two main functions: it slows down the vehicle and passes at a reduced velocity for unknown objects near the vehicle path and stops the vehicle for obstacles that are present on the vehicle path. The required deceleration that is needed to stop the vehicle in time depends on the vehicle velocity and the distance to the obstacle. If the obstacle is visible already far in advance, a smooth stop with moderate deceleration will result, if the obstacle is appearing closer to the vehicle more deceleration (within limits) is needed to stop in time.

Vehicle Control

Controlling driverless vehicles is a complex subject, in this paper only a broad overview is given. Vehicle control can be separated into two main topics: estimating the vehicle position from the combination of the set of odometric sensors and magnets, then controlling the vehicle in such a way that it follows a given route as good as possible. The following subsections are related to these topics.

Position initialization

When a vehicle is first switched on, its absolute position on the track is yet unknown. Within the infrastructure, special magnet series at a fixed distance are drilled, which have a unique magnet polarity pattern. When a vehicle moves over such a pattern, the magnet positions and polarities are measured and the absolute position of the vehicle is determined from the magnet database.

Position estimation

From the complete set of odometric sensors (wheel encoders, steer encoders, gyroscope), an estimate of the vehicle motion is computed every control cycle. By integrating the vehicle motion, the vehicle position estimate is updated.

Magnet correction

In combination with the vehicle (and thus sensor) position at the time of a magnet measurement, the absolute position of the magnet is determined. This sensed position is compared with the magnet position in a database and the deviation between the two is called the grid match, which is a measure of the accuracy of the position estimation.

Because the vehicle position estimate is computed from a set of motion sensors, it will eventually drift away from the actual position, e.g. due to wheel wear, steer encoder alignment errors, gyro drift. With every new magnet measurement, based on a number of grid matches, the vehicle position is slightly corrected to make sure the vehicle position estimate stays in line with the absolute coordinate system.

Route control

The routes the vehicle has to drive are distributed by TOMS to the various vehicles. These routes are distributed on the fly, meaning that a certain time before the vehicle needs to slow down to have zero velocity at the end of the route, a ‘near route end’ signal is sent to TOMS, which in turn sends a new route segment and as a result the vehicle can continue driving.

With the route and the actual position of the vehicle, the tracking controller inside the VCS computes the tracking error, which is a measure of the deviation from the route. The tracking controller uses a combination of feedforward and feedback to compute a velocity setpoint, a steering setpoint and a braking setpoint in such a way that the tracking error remains small.

Safety Aspects

The PRT vehicles are controlled using software, which of course has a lot of safety implications. Safety is an important subject that requires a lot of attention, but is out of the scope of this paper. But being crucial for the application, some words on the main safety aspects will be spent.

Safety circuits

Two hard wired safety circuits are present: a fast stop circuit and an emergency stop circuit. The fast stop circuit is intended to let the vehicle make a fast but controlled stop (vehicle does not deviate from the route). A fast stop can be applied from the passenger console or from the VCS.

Once the emergency stop circuit drops, the steering system will be fixed, the drive system will be switched off and the fail safe brake will be applied. Depending on the starting speed and direction some path deviation will occur, so this must be considered as a last resort if a controlled stop is expected to be not possible or safe anymore.

As the availability of the VCS plays a vital role in safety, there is a mechanism with a trigger signal used to keep the emergency stop circuit up and running. When the signal is not triggering anymore the emergency stop circuit will be automatically dropped as there is something wrong with the VCC, VCS, CAN bus or wiring.

VCS consistency checks

The vehicle control software uses a large number of checks to continuously determine the consistency of various components (encoders, gyroscope, steer servo, brakes, etc), check that the path deviation is within limits, the vehicle velocity does not deviate too much from the setpoint, internal software modules are valid, not too many magnets are missed, etc.

Depending on the severity of the failure of a check, a different action can be applied to each particular check, ranging from emergency stop, fast stop, normal stop, velocity restriction or warning to the operator.

External steer check

A central safety role is played by the VCS. If for some reason the internal computations in the VCS are incorrect, an external system is needed to prevent damage. The external steer check is used for this purpose. It checks if the steer angle and steer angle rate match the vehicle velocity. The basic idea behind this is that at high speeds the vehicle is not supposed to have a large steer angle. The check will drop the emergency stop circuit if the steer angle and steer angle rate are larger than certain velocity dependent limits.

Results

Test results are given in this section. Two operational scenarios are considered: Driving from Parking facility to MIST and vice versa.

Driving performance

The velocity profile of the two scenarios is plotted in the following figure.

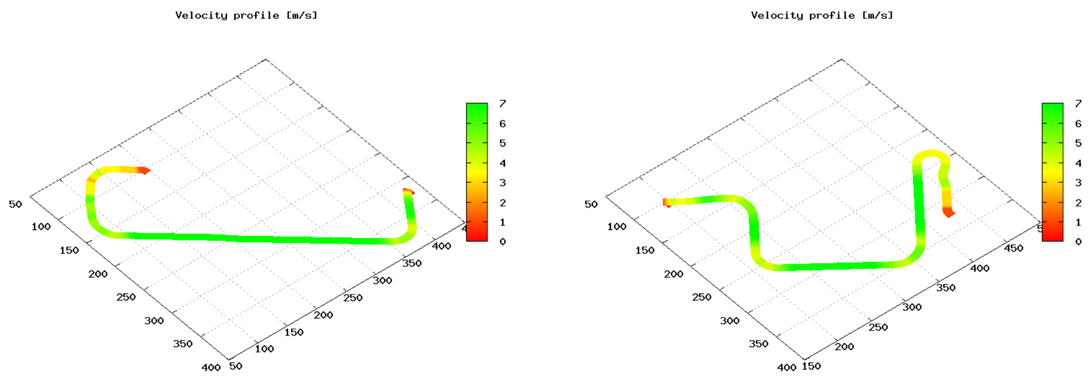

Figure 5 - Velocity profile

This figure shows that the vehicle slows down at the start and end of corners (limited by maximum steering speed), while in the corner a higher velocity can be achieved (limited by maximum lateral acceleration).

A summary of the scenarios is given in the following table, which shows that an average velocity of about 4 m/s is achieved.

Scenario	**Distance**	**Duration**	**Average velocity**
Parking facility to MIST	645m	154s	4.19 m/s
MIST to parking facility	684m	173s	3.95 m/s

Table 1 - Driving performance

Energy consumption

The energy consumption during the two trips is shown in the following figure. The positive power peaks are a result of acceleration of the vehicle and negative power consumption is achieved during regenerative braking. Interesting to see is that the energy consumption during the trip from parking facility to MIST is lower than vice versa, even though a higher average velocity is achieved. This is caused by this trip being somewhat longer, but also having more corners, so more fluctuations in acceleration and deceleration are needed.

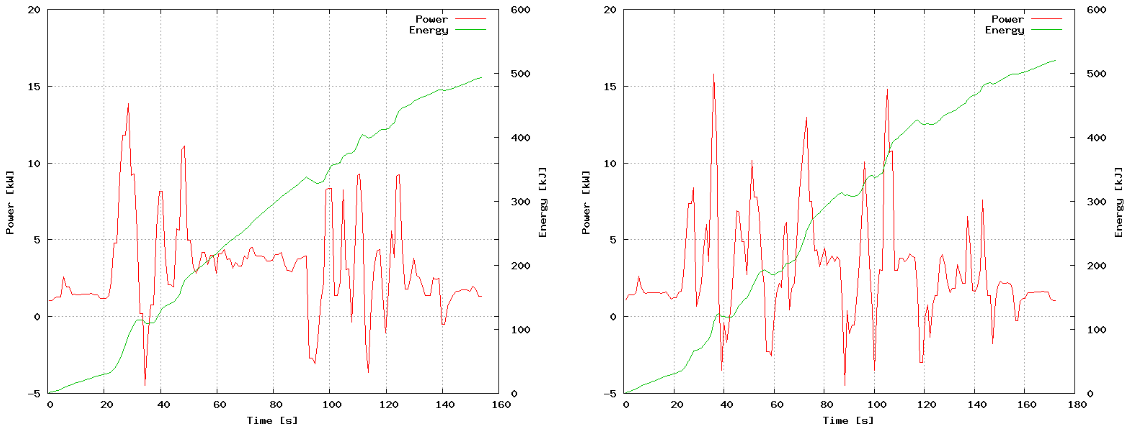

Figure 6 - Energy consumption (left: Parking to Mist, right: Mist to parking)

Driving accuracy

The following figure shows the distribution of the grid match for the two scenarios, which shows how accurately the vehicle knows its own position. Approximately 97% of the detected magnets are within 2 cm of the database position and more than 99.5% are within 3 cm (not only on straights but also in corners). The position corrections that result from each set of magnet measurements are even smaller (less than 1 cm), which is an indication that the accuracy at which the absolute vehicle position is known is in the same order.

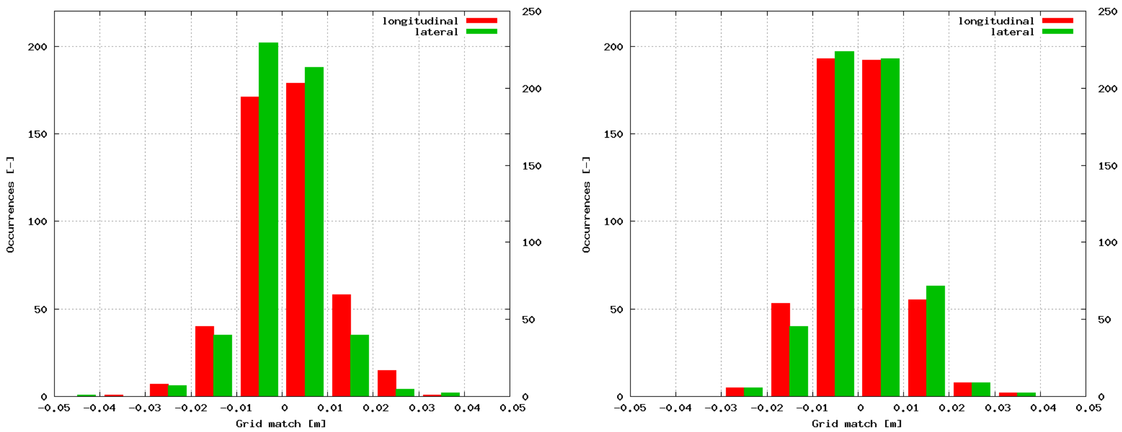

Figure 7 - Grid match (left: Parking to Mist, right: Mist to parking)

The tracking error in the following figure shows how much the vehicles deviate from the route. The tracking errors are largest when the vehicle is driving in reverse direction and in corners, but always well within the required boundary of 10 cm. Also note that near the stations before the berths are entered, the tracking error decreases within 2cm.

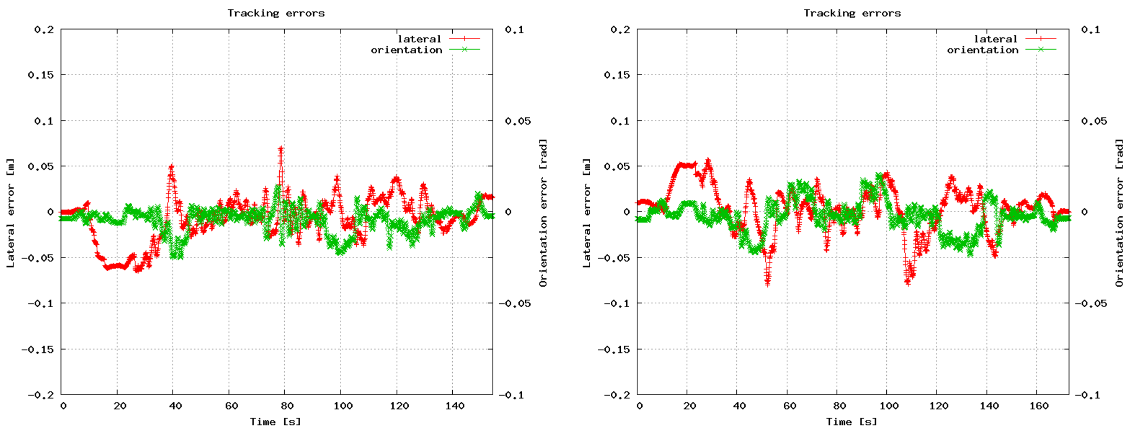

Figure 8 - Tracking error

Discussion

In this paper, the PRT vehicle architecture and control concept used in Masdar city is presented. It offers a fast, safe, comfortable and accurate way of guiding the driverless vehicles from start to destination.

The results that are presented in this paper show that position estimation using a combination of a redundant set of odometric measurements with magnet corrections is accurate and reliable and therefore well suited for this application. The control concept allows accurate guidance of the vehicles along the track, which is well within the limits required by the application.