ENABLING INTELLIGENT ALGORITHMS WITH NEW GENERATION SCANNING RADARS

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ABSTRACT

New scanning radar technology is making it possible to create a true representative image of vehicle and pedestrian behaviour. This technology has become cost effective and is now easily deployed and self configuring. It creates a real time dynamic image of every moving object within the zone of interest, tagging each vehicle and pedestrian with accurate size, location, speed, acceleration, and direction data.

Traffic control algorithms attempt to predict future traffic patterns or conditions by measuring recent past events. The effectiveness of these prediction models depends on the dimensions and resolution at which past events can be measured. The availability of these new advanced radar devices present an opportunity to the traffic engineer to improve these control algorithms with the accuracy and richness of the data generated by these radars.

The radar's ability to measure in five dimensions provide the Traffic Engineer with information about exact driver behaviour and create true learning machines delivering systems that could optimise traffic at intersections, freeways and cities for emissions, safety, delay, throughput and safety.

This paper introduces this new generation of radar system promise to revolutionise traffic control systems. The aim of the paper is to introduce the fundamentals of this technology and prompt Traffic Engineers to develop new models and systems to solve the challenges of tomorrow.

1. INTRODUCTION

Radars are fundamental in maintaining air traffic safety and improving air traffic management (Carletti, 2008). Air traffic control can increase their capacity by upgrading their radar systems. Improving the monitoring system directly allow them to improve air traffic safety and congestion management.

Advances in radar antennas and radar signal processing makes it possible to use radars with similar capabilities as air traffic radars on the road network. These advances were made possible by the exponential growth in sophistication of cellular phones and computer memory. The European Union have contributed substantially towards radar research for advancement in active collision avoidance for motor vehicles as part of their objective to reduce road fatalities. The processing power of personal computers and digital signal processors have maintained its exponential growth offering radar engineers processing power that were beyond comprehension ten years ago. All these developments resulted in a new generation of radar device that is cheap, small and exceptional accuracy. This new generation of radar uses digital beam steering techniques in order to measure the exact position of every vehicle without requiring a mechanical platform to rotate the radar beam. Scanning radars scan the environment by rotating the radar beam. Digital beam steering is a concept where the radar beam can be electronically steered to scan the area and discriminate vehicles and people at different angles.

Similar technology is currently being deployed in high end vehicles as a collision avoidance component as well as supporting advanced control functions to provide driver assistance.

Traditional traffic monitoring radars only measure speed and distance and do not have the ability to scan the environment to provide a complete picture of vehicles and pedestrians. Scanning radars combined with advanced processing technology to process the data provides a rich data set on which real time traffic management, optimisation, and measurement information may be derived.

Current real-time traffic control methods are based only on speed or presence information measured at a specific point on the road. What happens between the measurement points is often derived from predictive traffic models. Gap acceptance, deceleration, lane change and other behavioural properties of traffic is not evident with presence detectors.

In comparison scanning radars provides a real time, accurate picture of every moving object, each tagged, with size, speed, and acceleration. These objects are tracked by the software and exact driver behaviour is reported including gap acceptance, deceleration ad lane change behaviour. At intersections the formation and dispersing of platoons are evident. The rate, count and length that queues increase or decrease can be provided. The delay that each vehicle experiences at intersections can be provided. Exact merging manoeuvres can be provided for ramp metering applications.

Scanning radars offer traffic engineers the ability to reinvent solutions to today’s challenging traffic problems.

2. DETECTION DIMENSIONS

These scanning radar sensors are capable of measuring five dimensions. (Brooke, 2006)

2.1. Presence

Radar sensors can measure the presence or absence of a retro-reflector. A retro-reflector is any object that allows the signal from the radar to be bounced back to the radar. The Radio Cross Section (RCS) of a reflector represent the amount of radio energy that is retro-reflected. Some radio energy is not retro-reflected because it is absorbed by the object or reflected away from the radar. Larger objects are likely to reflect more radio energy. Motor cars typically reflect 3 times more radio energy at 24GHz than a human. Stealth aircraft attempts to reduce the RCS of the aircraft by minimising retro-reflective surfaces on the aircraft. If the distance to a vehicle is known then the RCS for similar vehicles are proportional to the size of the vehicle. The returned signal strength is also affected by the distance to the object. The range capability of radar is determined by the power of the transmitter and the sensitivity of the receiver.

Inductive loops that are the de-facto standard vehicle detector measure only one dimension: Permeability (Jackson, 1975). Permeability is translated to vehicle presence. If vehicle presence is measured at two points then vehicle speed could be calculated. Occupancy and Density can be estimated by referencing presence measurements over time. Density refers to the number of vehicles over a stretch of road. Density can be determined from a presence sensor only when each vehicle travels at a constant speed. Zero acceleration is thus a requirement for accurate density calculation using an inductive loop. Traffic management is particularly interested in changes in traffic flow because a change in strategy is needed to deal with changes in traffic. Thus using presence alone does not provide dynamic real-time information about vehicles and traffic.

2.2. Velocity

Radars measure the Doppler Effect. Doppler is the difference in returned frequency caused by the fact that the vehicle is travelling towards or away from the radar. This frequency difference is directly proportional to the Radial velocity of the vehicle. (Filkin, 1997). If the location of the target is known the radial velocity can be transformed to true velocity at accuracy of better than 1km/h.

2.3. Distance

Radars measure distance by determining the amount of time a signal takes to travel to the vehicle and back. The electromagnetic wave of radars travels at a constant velocity. Military Pulsed Radars measure the return time of the radio pulse being reflected off an aeroplane. For distances less than 1 km another method called Frequency Modulated Continuous Wave (FMCW) is used. With this method a linear frequency chirp is transmitted. The received chirp is delayed by a time that is proportional to the distance. If the receiving frequency is subtracted from the transmitted one the result represent the distance (Brooke, 2006) A distance resolution of less than 10mm can be achieved with this method.

2.4. Angle

In military applications a rotating platform is used to scan an area. This method makes it possible to measure the angular position of an object. Rotating platforms are not practical for traffic monitoring due to its cost and mechanical maintenance requirements.

Digital Beamforming is a technique that uses interference on more than one antenna to electronically rotate the radar beam. This is achieved by controlling the amplitude or phase angle or the signal. Through the reciprocity principle the received signal can also be steered. Radars are therefore able to measure the angular position of a vehicle or a number of vehicles. (Groves, 1997) Collision avoidance radars on motor cars use digital beamforming to be able to monitor other vehicles and objects around the road and their respective locations.
Angle measurements in traffic monitor applications provide the ability to distinguish vehicles in different lanes. Polar coordinates from angular and distance measurements are converted to rectangular coordinates that correspond to the true GPS location of each vehicle.

2.5. Vehicle length

A number of reflections are received from each vehicle. The relative distance between these reflections can be measured by a signal processing algorithm. This distance is projected distance, because the radar does not know instantaneously what the orientation is of the vehicle. At the next measurement cycle the radar can determine the heading of the vehicle and is then able to translate the projected distance to real vehicle length. Measurement cycles are typically 50 milliseconds long.

2.6. Benefits

Some dimensions can be correlated. Dimensional correlation offers the following benefits:

- More accurate measurements;
- More resilient against environmental influences;
- More flexible installation locations;
- Improved reliability offered through redundancy of dimensions;

The Scanning radar's ability to measure five dimensions offers the following key benefits:

- Ability to measure trajectory of each vehicle;
- Ability to measure reaction time and deceleration profile of vehicles at intersections;
- Improved ability to estimate emissions;
- Ability to monitor merging and other lane change manoeuvres;
- Ability to derive individual vehicle service level;

3. DETECTION TECHNOLOGY COMPARISON

The Federal Highway Administration has published a report (FHWA, 2007) comparing the different vehicle detection technologies. This report did not include scanning radar technology presented here. Table 2 indicate how these different detector technologies compare in terms of the dimensions that they measure. Dimensions that are derived from measured dimensions are not indicated. Magnetometers and cross fire radars can for example derive velocity from a presence measurement. It is necessary to assume that all vehicles are 4m long. The presence period then roughly correspond to the speed.

The versatility is proportional to the number of measurable dimensions as can be seen in Table 1. The number of dimensions for radar sensors is also proportional to the Usability of the sensor. The velocity measurement can be correlated with the change in position. This internal correlation makes the sensor resilient against different installation anomalies and operational anomalies.

	Presence / Intensity	Velocity	Distance	Angle	Vehicle length
	Measurement Dimensions				
New generation radar	X	X	X	X	X
Traditional radar		X	X		
Video	X			X	X
Acoustic	X	X			
Passive Infrared	X				
Laser scanner	X		X	X	X
Active Infrared	X	X	X		
Magnetometer	X				
Dual Inductive loop	X	X	-		X
Piezo		X			X

Table 1: Dimension Comparison of Different Detector Technologies

	Dimensions	Operate in all weather conditions	Detect Slow/Stopped Traffic	Do not require regular Maintenance/Cleaning	Temperature stability	Dependency	Classification	Do not require pavement cut	Speed, Count and Presence detection	Trajectory measurement	Do not require physical sensor positioning	Large area coverage
		Usability					Capability					
New generation radar	5	X	X	X	X	X	X	X	X	X	X	X
Traditional radar	2	X		X	X	X	X	X			X	
Video	3		X		X		X	X	X	X	X	
Acoustic	2							X				
Passive Infrared	1							X				
Laser scanner	4		X		X		X	X	X	X	X	
Active Infrared	3		X		X		X	X	X		X	
Magnetometer	1	X	X	X					X			
Inductive loop	3	X	X	X			X		X			
Piezo	2	X	X	X			X		X			

Table 2: Usability and Capability Comparison of Different Detector Technologies

3.1. Traditional radar

Traditional radar sensors are either configured for cross-fire or forward-fire. Cross-fire means that it installed at a right angle to the road. Cross fire radars measures change in presence similar to inductive loops. Such radars can detect up to 12 lanes but only measure presence, distance. Distance is used to determine in which lane the presence measurement was made. Occlusion is a major problem with cross fire radars because there is only one moment in time and space that the radar has to detect the presence of a vehicle.

Forward fire radars on the other hand are capable of measuring traffic acceleration, speed and distance over a stretch of road but cannot distinguish between vehicles in different lanes. In order to distinguish vehicles in different lanes it is necessary to measure the angle to the vehicle. These radars could produce worst than 40% accuracy because they are unable to distinguish between 1 vehicle, 2 vehicles or 3 vehicles next to each other on a 3 lane road.

This crucial ability of measuring the angle sets new generation radars apart from existing radars.

3.2. Video detectors

Video Image Processing Detectors measure only three dimensions namely intensity, projected X and projected Y position. Video detection resolution deteriorates exponentially over distance, because the position information is projected from a perspective view onto the camera sensor. The intensity is a rough indication presence and is affected by a number of environmental influences such as rain, seasonal sun glare and shadows. These effects influence the video detectors ability to separate vehicles. Video detectors also have to be mounted very high in order to minimise the impact of the projection error. To minimise these effects video detectors typically operate on very short distances and in applications where operation in severe weather is not critical.

3.3. Scanning radar

Figure 1 indicates the relative size of new generation scanning radar. Collision avoidance radars are capable of detecting up to 32 simultaneous targets over an area covering up to 9 lanes and a distance of 240 meters. A single instance of a target or vehicle could be detected within 300mm and 0.1 degrees. An improved version of this radar is capable of detecting over 100 simultaneous targets. This radar is capable of scanning the complete area in less than 50 milliseconds. Therefore each vehicle travelling at 60 km/h is seen every 830 mm. A tracking algorithm is used to calculate the exact trajectory of each vehicle over this distance. Therefore exact speeds, acceleration, lane changes, merging manoeuvres and collision avoidance manoeuvres are observable.

Figure 1: Scanning radar installed in Malmesbury

Figure 2 shows an instantaneous plotting of the data content from the radar. The video images are shown to assist correlation of the radar data with video images. Each vehicle is assigned a unique ID when it enters the view of the radar and that ID is maintained until it exits the view of the radar. The line on each vehicle is proportional to its speed and the direction of the line proportional to its heading. The heading information is derived from the tracking algorithm.

The radar produces accurate data over its entire field of view. Shadows, heat shimmer, and visibility effects result in poor video visibility at the radar extents even though the 3 megapixel camera theoretically offer 11 pixels per meter at the same angle of vision than the radar.

These radars were installed at approximately 6 meter height. Vehicles at the stop line are indistinguishable using video cameras, but the rich dimension-depth of the radar allows these vehicles to be easily distinguishable. The ability to measure acceleration and deceleration is another useful capability of scanning radars.

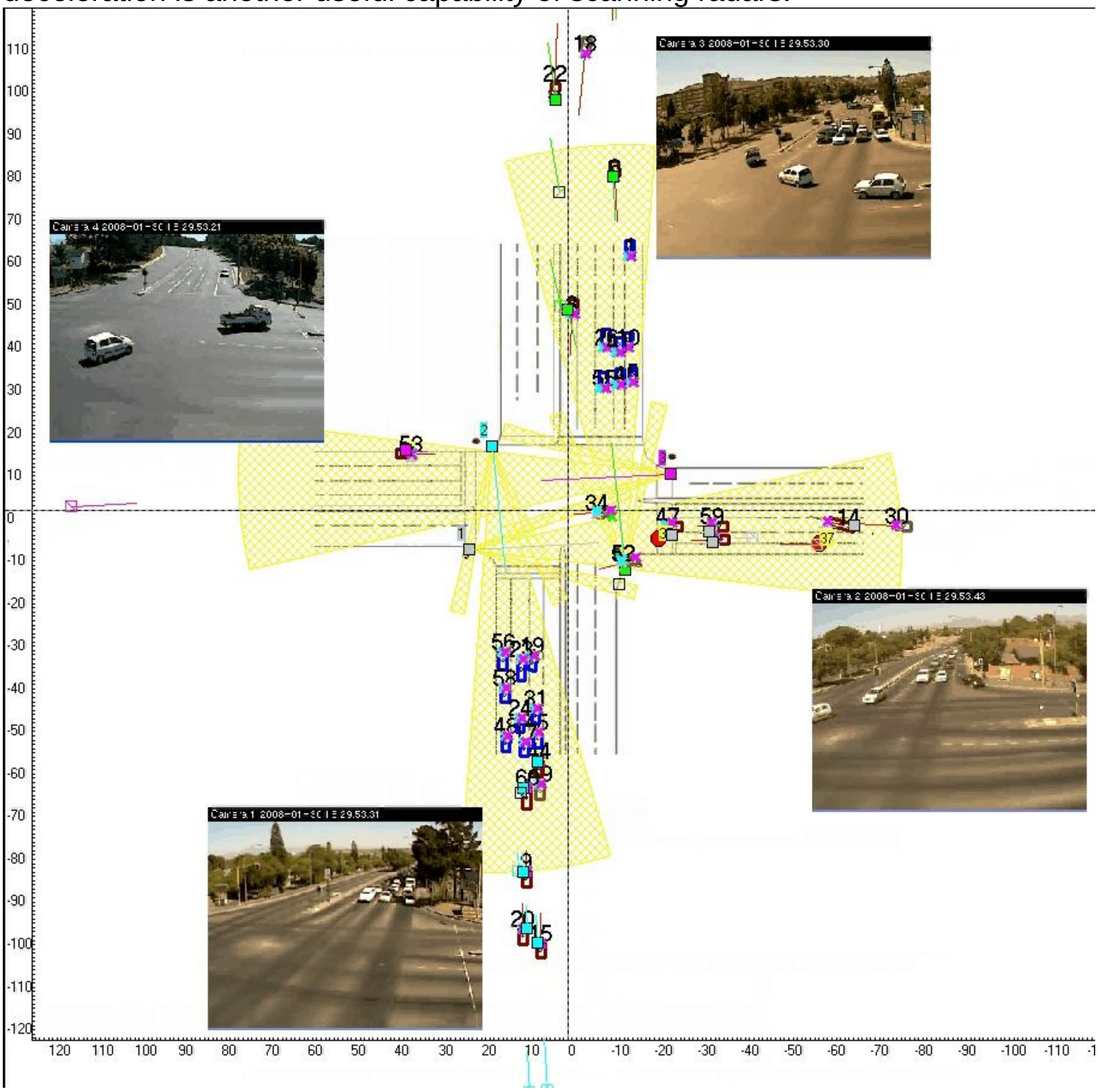

Figure 2: One 50ms measurement frame at an intersection in Cape Town. Each tracked target (vehicle) is assigned an ID shown next to each square. The ID is maintained as long as the vehicle is within 240m from the intersection. The velocity and vehicle length is known for each vehicle and each instance.

4. AREAS OF APPLICATION

4.1. Traffic Signal Adaptive Control

Traffic Signal Adaptive Control Systems has to achieve traffic delay and flow objectives for an area or corridor during changes in traffic demand. (Young, 1989). Traffic has a metastable property. Traffic flow tends to settle into stable patterns when there are no external influences. External influences such as traffic light changes or change in demand create a disturbance that has a knock-on effect on future traffic until another metastable state is achieved.

The requirements of an adaptive control system are:

- To be able to effectively predict demand
- To be able to effectively predict the future outcome of intended actions per intersection and per area/corridor
- To be able to coordinate control over the area or corridor
- To be able to maximise the use of available time/space

Predictability is a fundamental objective. Prediction is based on past measurements as well as certain constants. Although prediction models in different adaptive systems such as SCOOT and SCATS differ considerably they still base their predictions on recent past traffic measurements. These measurements are all based on a single dimensional inductive loop sensor. Thus they have to extrapolate their single point in space measurement to a larger area of road to predict unstable traffic behaviour. The result is then used further to predict traffic forward in time.

Scanning radar measures what current adaptive control systems extrapolate. It measures platoon dispersion and actual vehicle behaviour over the full length and breadth of the road. It constantly measures lane change manoeuvres. Measuring individual vehicle behaviour such as individual lane changes is often a good indication of future changes in demand. Platoon dispersal could be a good indication of future change in demand.

Scanning radars constantly measure queue lengths and the rate at which queues grow. The question of when a vehicle queued becomes much more complicated when the complete trajectory of the vehicle is known. A possible answer is that a vehicle is queued when the vehicle has to decelerate at a certain rate where the road geometry does not necessitate slowing down at that rate. The driver was in other words discomforted. Another possible answer is that a vehicle is queued when the vehicle is could be to consider a vehicle joining when the following distance and speed is below certain minimum.

Another primary objective of Adaptive Control Systems is to increase safety at traffic lights. Signalised intersections are particularly unsafe due to the large speed differential between opposing approaches. Scanning radar is suitable to implement Dilemma Zone (Saito, Ooyama, & Sigeta, 1990) Control in a way that does not reduce traffic flow efficiency. The time to arrival can be accurately predicted by looking at the deceleration as well as change in deceleration over time. Deceleration differences between vehicles in the same lane can also be monitored. The control algorithm can therefore trigger light changes when there is a minimum chance for a vehicle to run into the rear of another as well as reducing red light running.

A safety strategy is to keep the all-red stage when the time to arrival of a vehicle is past the inter-green time. From measurement of deceleration profiles we have found that in most instances we could predict red light running more than 8 seconds before it occurs.

Another objective is minimising of emissions at signalised intersections. Current systems use vehicle counts and red time to estimate emissions. With scanning radar it is possible to measure the delay of each vehicle thereby providing much more accurate input. The radar can also measure acceleration and vehicle length. Both delays and deceleration can be minimised using the information from the scanning radar. Further research is required in this field using scanning radars.

4.2. Ramp Metering

The purpose of a ramp metering system is to reduce freeway congestion by breaking up platoons and controlling the feeders whereby flow rate on the freeway can be controlled. Existing control systems use inductive loops to calculate flow, speed and occupancy on both the freeway and ramp. The current feed-forward, open loop and feedback control systems all model gap acceptance. Current systems therefore use generalisation for gap acceptance and uses rough estimations of how much mainstream capacity would be used by every control action.

Scanning radar continuously measures gap acceptance as well as how the ramp feeder affects the platoon dispersion. With this level of detail it is possible to continuously train a micro-simulation model that could greatly improve the determinism and accuracy by which traffic is fed to the main stream.

Improved methods to measure traffic fluidity could be developed using individual vehicle acceleration and deceleration trajectories on the freeway

4.3. Incident Detection

Current Incident detectors measure occupancy, speed and volume at a particular point on the road. False incident warnings are indirectly proportional to the severity of the incidents. An incident is considered an average reduction in speed when the average volume does not warrant such a reduction in speed. Average speeds could vary a lot depending on measurement bin size, type of traffic, weather and road conditions.

With scanning radar every vehicle's deceleration is measured. Could an incident be classified as a deceleration threshold being exceeded for a certain percentage of vehicles? It may be possible to consider percentage vehicles changing lanes as a parameter contributing towards detection of incidents. It is possible to consider which vehicles decelerated due to slower moving traffic ahead or slowing down traffic ahead. This is because speed and deceleration is known for each vehicle. The trajectory of each vehicle could provide engineers with better data to determine incidents and the severity of incidents with better accuracy.

5. CURRENT DEPLOYMENTS AND RESEARCH

The use of scanning radar for vehicle detection is limited worldwide because until recently these radars were very expensive. The collision avoidance industry focused on 76GHz sensors. At this frequency components are still very expensive. Only recently have 24GHz scanning radars become available.

Known users of scanning radars in traffic are:

- University of California Berkeley - Cooperative Intersection Collision Avoidance Systems (CICAS) Research
- Traffic Management Technologies – iControl installations in Malmesbury, Cape Town and Durban
- Navtech radar – Tunnel monitoring installations with a mechanically scanning radar
- Jenoptik – Intersection enforcement cameras based on scanning radar
- University of Stellenbosch – 4th Year project to demonstrate intersection collision avoidance capablity

6. CONCLUSIONS

Scanning radars offer detailed trajectory information about every vehicle. It has the ability to track vehicles over a large area with precision. The radar is more flexible, more reliable and more practical, because it measures in five dimensions. These new generation radar devices offer new opportunities to Traffic Engineers to solve difficult traffic safety, emissions and congestion problems. Traffic Engineers should therefore consider deploying these sensors for experimental and operational purposes.
Engineers can also use scanning radars as research tools to measure and record actual driver behaviour.

The areas of application that are currently foreseen are:
- Adaptive control of traffic signals;
- Ramp metering
- Incident detection
- Research and monitoring

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