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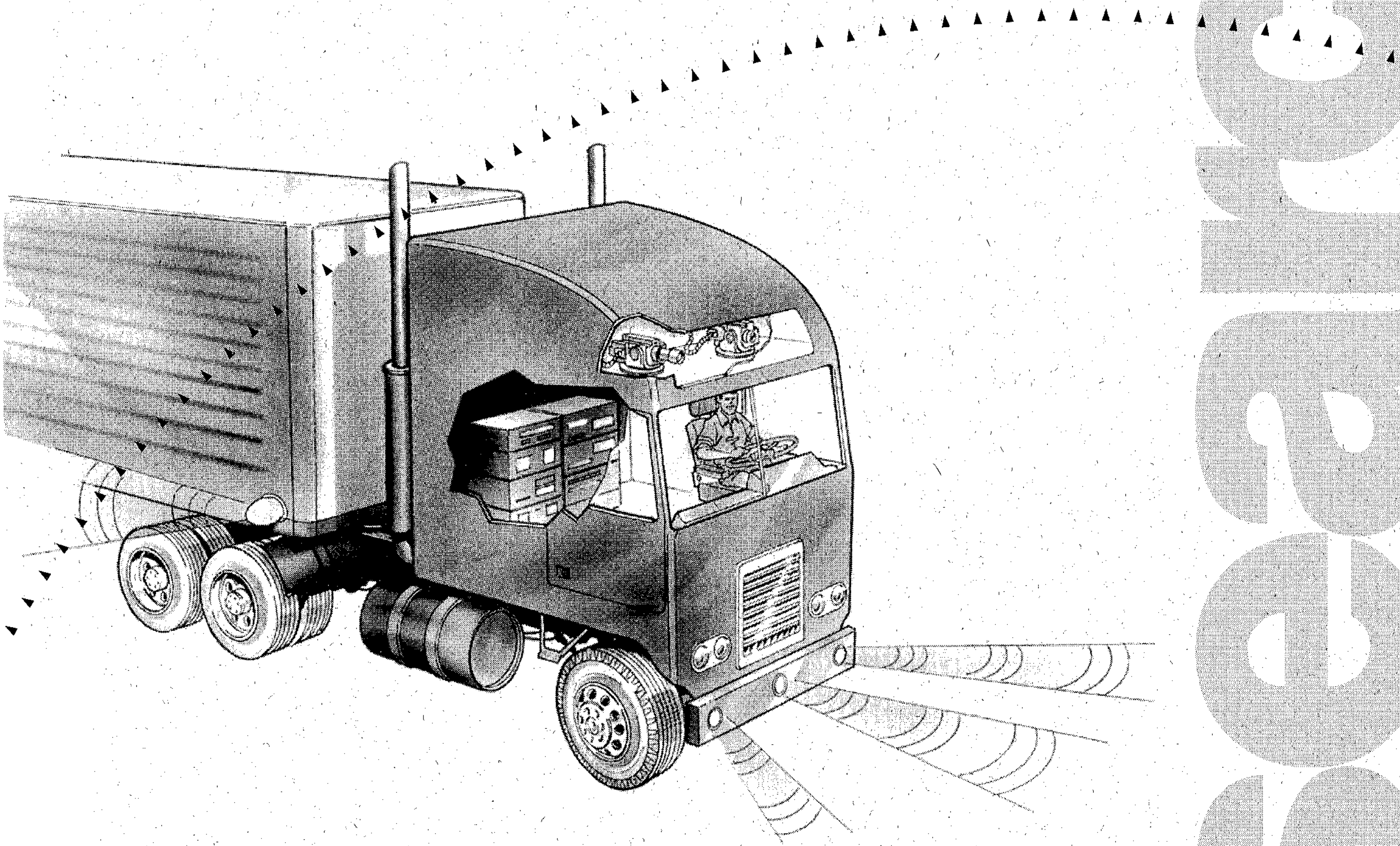

Research

MIMIC Sensor Technology for Highway Vehicle Applications: Potential and Challenges for the Future

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Recent advances in MIMIC (**MI**llimeter **M**onolithic **I**ntegrated Circuit) radar technology play an important role in the development of automated highway systems and automated vehicle control systems. This report presents results of a preliminary investigation into MIMIC-based automotive radar technology and makes recommendations for hardware evaluation.

MIMIC technology integrates much of the radar transmitted, receiver, and signal processing hardware onto a one- or two-piece chip set. Massive integration leads to lower manufacturing costs and lower product costs. Moreover, this integration reduces the size of hardware, allowing the radar components to be installed in the vehicle without the need for significant modifications. As radar systems become smaller and cheaper, the demand for these systems will increase.

Radar systems affect both the vehicles so equipped and other vehicles within a reasonable proximity. Before vehicles equipped with radar systems travel on public roads, their effects on traffic flow and highway safety must be investigated so that proper regulations can be developed and enforced.

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MIMIC Sensor Technology for Highway Vehicle Applications: Potential and Challenges for the Future

Final Report

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Executive Summary

Radar technology will play a significant role in both the Automated Highway Systems (AHS) and the Automated Vehicle Control Systems (AVCS) areas of the national IVHS initiative. Although the idea of using automotive radar for collision avoidance has a long history, widespread deployment is becoming closer to reality because of recent advances in MIMIC (MIllimeter Monolithic Integrated Circuit) radar technology. MIMIC technology integrates much of the radar transmitter, receiver, and signal processing hardware onto a one or two piece chip set. As with any electronic device, massive integration leads to lower manufacturing costs, and therefore lower product costs. Moreover, this integration reduces the size of hardware, which allows the radar components to be installed in the vehicle without the need for significant modifications. As radar systems become smaller and less expensive, the demand for these systems will increase.

Radar systems affect both the vehicles so equipped and other vehicles within a reasonable proximity. Before vehicles equipped with radar systems are allowed on public roads, their effects on traffic flow and highway safety must be investigated so that proper regulations can be developed and enforced. The results of a preliminary investigation into MIMIC based automotive radar technology are presented. From these results, recommendations for hardware evaluation of three radar systems are made. The recommended hardware to be investigated includes a system presently commercially available, a MIMIC based system specifically developed for automotive use, and a MIMIC based system developed for military applications but with significant commercial potential.

Key words: Automotive Radar, MIMIC, Collision Avoidance, Automated Highway Systems, Advanced Vehicle Control Systems

I. Introduction

The Intelligent Vehicle and Highway Systems (IVHS) program underway in the United States promises to radically change the methods with which goods and people are transported throughout the country. These changes will arise from the application of emerging computer control and communication technologies to both vehicles and the transportation infrastructure. Activities under the IVHS umbrella include Advanced Traveler Information Systems (ATIS) which provide travelers real time information regarding highway conditions, traffic levels, construction, etc.; Advance Traffic Management Systems (ATMS) which are designed to manage heavily used highways and arterials by regulating the influx and outflow of vehicles on the roadway; Commercial Vehicle Operations (CVO) which are designed to streamline both intrastate and interstate trucking operations by providing services such as "weigh in motion" to monitor the gross vehicle weight of heavy trucks; Advanced Rural Transportation Systems (ARTS) which are designed to improve the safety and efficiency of rural transportation through the application of technology such as emergency transponders for vehicles traveling in lightly populated areas; and Advanced Vehicle Control Systems (AVCS) which are designed to assist the driver with vehicle control tasks such as intelligent speed regulation, obstacle detection and avoidance, merging, and in-vehicle route planning on present roads (or roads with minor modifications to what exists today). Automated Highway Systems (AHS), which deal with highway lanes dedicated to vehicles with special control capability, is distinct from all the rest. AHS represents a demonstration prototype for future highways. Many of the systems proposed under IVHS, (i.e., ATIS, ATMS, CVO, AVCS), will find their way into AHS.

Radar technology will play a significant role in both AHS and IVHS because of recent advances in MIllimeter Monolithic Integrated Circuit (MIMIC) radar technology. MIMIC technology integrates much of the radar transmitter, receiver, and signal processing hardware onto a one or two piece chip set. As with any electronic device, massive integration leads to lower manufacturing costs, and therefore lower product costs. Moreover, this integration reduces the size of hardware, which allows room for the radar components in the vehicle without adversely affecting the vehicle design. As radar systems become smaller and less expensive, the demand for these systems will continue to grow.

Much of the work done regarding AHS deals with "platoons" of vehicles which travel at high speeds with vehicles in close proximity to one another. A number of scenarios have been proposed and analyzed. One scenario involves a communication system between the lead vehicle and the following vehicles. In this arrangement, the lead vehicle issues vehicle control commands to the other vehicles associated with the platoon. This arrangement offers high performance in terms of (small) intervehicle spacing, but at the expense and complexity of the added communication system. Radar systems offer an alternative to intervehicle communication systems. In this arrangement, each vehicle (except, of course, for the lead vehicle) uses the vehicle directly ahead as a reference from which to generate vehicle control commands. The complexity of intervehicle communications is eliminated, but intervehicle spacing performance suffers due to the "accordion effect" which arises due to sensing and control lags between each vehicle. One recent development to reduce the accordion effect is to use both front and rear radar to maintain the proper vehicle spacing. Use of the rear looking radar allows the vehicle controller to "equalize" the gap between both the front and the rear vehicles. Improvements in platooning performance via the addition of rear looking radar have been recently demonstrated [Tongue, 1994].

Under many circumstances, response characteristics needed to sense the unexpected, make decisions and take action necessary to avoid collisions are such that humans cannot react quickly enough. In such cases, autonomous control of the vehicle is required. It is our contention that such autonomous behavior must be operative in a manner transparent to the driver so that the vehicle can respond to dangerous situations even when the driver cannot. The concept of driver supervised autonomous vehicles operating on standard roadways poses a more challenging problem to radar systems than does platooning on a dedicated lane. Radar systems operating on standard roadways must not only "look" forward, but will have to look into turns, look to the sides and to the rear in order to avoid collisions during "routine" lane changing, merging, and obstacle avoidance maneuvers. Such systems will consist of antenna arrays of sufficient size and flexibility to sense the periphery of the vehicle and signal processing hardware and software capable of operating in real time (i.e., fast enough to provide both the driver and control computer with data so that necessary maneuvers can be computed and executed). Much of the raw technology is available to handle such a system (processing rates, multiple antenna arrays, etc.); however, an actual implementation of such technology on an operational highway vehicle has yet to occur.

The main impetus for the development and deployment of an autonomous control capability for highway vehicles is safety. According to the National Highway Traffic Safety Administration (NHTSA), drowsy drivers cause up to 600,000 accidents and 12,000 fatalities every year. In Minnesota, which uses a different method of accounting, of the 165,000 drivers involved in crashes in 1992, 900 were cited to be asleep or fatigued [AAA, 1994]. To combat the fatigue, a vehicle controller capable of "driving" under conditions which typically lead to drowsiness (long stretches of monotonous highway, for example) can also be used to relieve the driver of the tedium associated with driving under such circumstances. This would be of particular application to rural roads.

The results of IVHS research are important to Mn/DOT for a number of reasons. First, Mn/DOT is responsible for the safe transportation of goods and people across the state. To ensure the public safety, Mn/DOT has to know the potential increase (or decrease, as the case may be) to driver, passenger, and cargo safety and the effects on pedestrian safety and vehicle performance which arise from these technologies. Second, Mn/DOT is responsible for the regulation of vehicle systems in the state, and the state legislature is responsible for enacting laws which ensure the safety of Minnesotans. To make intelligent regulatory decisions, the governing body must understand to what extent technology applied to highway vehicles will affect transportation in the state. Finally, Mn/DOT will eventually have to decide whether to build special automated highway lanes to accommodate vehicles designed to operate on such roads, or whether not to dedicate special lanes, but to allow some form of autonomous vehicle control to operate on standard highways.

II. Automotive Radar

Navigation and collision avoidance constitute the primary objectives of the driving task, and account for the majority of effort required to drive. Although collision avoidance normally represents a subconscious task of the driver, it becomes a very conscious task in emergency situations. To be successful, automotive radar systems must emulate both these conscious and subconscious efforts.

Vehicular radar systems can be broken down into 4 categories; each category represents a more difficult task. The four categories may be described as follows:

- **Driver warning systems** indicate a safe following distance to the vehicle ahead and warn the driver of inadequate following distance or excessive closing rates to the vehicle ahead. VORAD produces a system which provides a warning for unsafe vehicle following; a side looking "blind spot" monitor is optional. This system has been installed on 2400 Greyhound buses, and uses a system of green, yellow, and red lights combined with audible signals to provide the driver additional time to make decisions regarding braking, throttle, and steering actions.

- **Intelligent Cruise Control** (ICC) uses forward looking radar, infrared, or laser sensors to automatically maintain the proper vehicle spacing instead of just regulating vehicle speed as is done with traditional cruise control. Instead, ICC looks ahead to determine distance and closing rates, and adjusts throttle position to maintain safe headway. If changes in throttle position fail to provide adequate deceleration, ICC can force the automatic transmission to shift to lower gears, invoking engine braking. Leica of Germany has installed an ICC system on a fleet of Saab 9000's and has demonstrated this system both in Europe and the U.S. A description of the Leica system is provided in the following section.

- **Forward Collision Avoidance** detects obstacles in the forward path of a vehicle and provides information regarding heading and closing rates for those obstacles. This category includes driver assistance schemes where the suggested collision avoidance countermeasures are provided to the driver via a Head Up Display (HUD) and automatic systems where the vehicle controller processes sensor information to compute and execute the best collision avoidance countermeasure.

- **Autonomous Collision Avoidance** incorporates a radar array placed on the periphery of the vehicle to provide real time maps of the local environment. With adequate real local maps, the vehicle control computer can execute collision avoidance maneuvers without external input from the driver. Such a system can automatically compute and execute merging, braking, and safe lane change maneuvers.

At this time, the authors know of no implementations of category three or four systems in hardware on a vehicle. The lack of available category three or four systems arises from current deficiencies in both affordable radar hardware and high performance signal processing systems.

To put the current state of the art into perspective, automotive radar systems from Europe, Japan, and the United States will be discussed.

Europe. A number of European companies have been involved in automotive radar and vehicle control, notably Philips and Leica. These companies are the only ones who publish in this area in U.S. technical journals. Phillips [Stone, 1992] has focused on 94 GHz FMCW (Frequency Modulated Continuous Wave) radar for automotive applications. Military millimeter wave (MW) radar typically operates at 94 GHz, and therefore equipment which operates at this frequency is readily available. The 94 GHz center frequency differs with the 77 GHz center frequency allocated to the European PROMETHEUS and DRIVE programs in Europe. Philips has developed and demonstrated a FMCW radar unit 100 mm long with an antenna of 150 mm aperture for automotive applications. This unit has an angular resolution of 1.5 °, and draws 10 mW of power while providing a usable range of 128 m. Philips has not performed any vehicle integration, but has worked to optimize radar beam shapes for automotive use. What makes Philips unique in the world of 94 GHz FMCW radar is their antenna manufacturing capability. Philips uses an injection molded antenna for its radar; the injection molding process is adapted from their compact disc manufacturing process, and yields a very inexpensive antenna. Their ability to manufacture low cost antennae puts them into a competitive position.

Leica [Leica, 1994] has used infrared (IR) laser to develop an ICC system. The transmitter/receiver package is 99 mm x 84 mm x 110 mm, uses the time of flight principle, has a range of 150 m, and has a typical accuracy of ± 0.2 m and ±1.6 km/hr. The beam angle is 3°, and the system provides distance and relative velocity to the target information at a rate of 10 Hz. Leica has integrated this sensor technology with a vehicle longitudinal controller. The University of Michigan Transportation Research Institute (UMTRI) has one of these Saabs, and demonstrated the vehicle in the U.S. at the "Workshop on Collision Avoidance Systems," which was sponsored by the IVHS America Safety and Human Factors Committee and the National Highway Traffic Safety Administration (NHTSA). This workshop was held in Reston, VA, March 21-22, 1994. One of the authors drove this vehicle and found its performance to be rather impressive in straight-line highway situations. Other unbiased drivers have also indicated that the vehicle performs well during heavy rain and at night. However, turns prove problematic. Because the IR system is designed to only look directly ahead of the vehicle, the system would lose "lock" on the vehicle directly ahead during cornering. Detecting no vehicle ahead, the control system would issue a command to resume the desired "obstacle free speed." In response to this command, the Saab would accelerate strongly in the curve until the vehicle ahead was detected, at which time speed regulation would re-occur. For corners with small radii, this detection would occur at a distance less than acceptable for safe following. Depending on the radius of the curve, this behavior can become rather annoying, and could lead to a lack of driver acceptance. Leica's options at this point include mechanically rotating the sensor head in phase with the front wheels, but this would add to the system cost and decrease the reliability of the system. At this time, Leica has not indicated that it will pursue these options. Radar solutions to losing IR sensor "lock" will be discussed in section III.

Japan. Very few technical papers regarding automotive radar systems have come from Japan. This may be for two reasons. First, they may not wish to "show their hand" on what could be a very important (and potentially high volume) option for automobiles. In this market, being first with a radar system may result in increased sales. Second, since W.W. II, the Japanese defense industry has been essentially nonexistent. Most of 70-100 GHz radar technology available today has been developed for military applications under secret or classified programs. The Japanese would have little or no access to the developments arising from these military projects which would explain Japan's apparent lack of significant effort in this area.

One paper regarding Japanese radar was located and studied [Kotaki, 1992]. In this publication, three radar systems were evaluated to determine their applicability to automotive radar. FMCW radar operating at 50 and 70 GHz were evaluated as was a Pulse Doppler unit operating at 60 GHz. Nothing unexpected was reported.

United States. General Motors subsidiaries Delco Electronics and Hughes Electronics have teamed up to build a school bus radar based warning system known as FOREWARN [FORE, 1994]. This system uses low power radar to continuously check for the presence of children in front of the bus or on the right side of the bus during the time when the "STOP" arm on the left side of the bus is out. An 8-12' wide, 4.5' high, and 15' long volume is sensed both in front and on the right side of the vehicle. Left side and rear looking radar is an option. The standard 2 sensor package sells for $1585 (hardware only, installation additional). FOREWARN is approved for use on school buses in more than 35 states.

Individual school districts determine which safety devices in addition to those required by state law are installed on district buses. Certain devices and procedures, however, qualify for a subsidy taken from the "reserve funds for school bus safety." In the past, the Minnesota Department of Education determined what devices qualified for the subsidy; the determination was made by the equipment subcommittee. In the recent past, the State Legislature has taken the responsibility for school bus safety equipment away from the Department of Education (and as a byproduct, eliminated the need for the equipment subcommittee), and assigned responsibility to the Department of Public Safety. As a result, FOREWARN has not been formally approved for use in Minnesota, nor is its use prohibited. FOREWARN may be installed on school buses, but it does not qualify for a subsidy.

VORAD, a system designed to assist drivers in maintaining a proper headway between vehicles by warning drivers of excessive closing rates or inadequate headway is presently available to operators of large fleets of heavy vehicles. Greyhound bus lines, who have installed VORAD on all of their interstate buses, have made favorable reports on the performance of the system [Sharn, 1992]. Eaton Corporation, which recently acquired VORAD, has worked to adapt the VORAD system for use in ICC, but the results of that effort have not been made public [Smedley, 1994].

Other radar vendors (TRW, Rockwell, Raytheon, and HE Microwave (a subsidiary of Delco and Hughes Electronics)) have been working to adapt military versions of millimeter wave radar for automotive applications. However, the adaptation of military radar to automotive applications poses a number of problems.

Radar antenna size is inversely proportional to the frequency at which the radar operates; as frequencies increase, the required size of the antenna decreases. Having large radomes on the grills of cars fails to appeal to a large segment of the car buying population. For instance, the VORAD system, which operates at 24.5 GHz, requires a radome 8.1 in. x 6.7 in. x 5.1 in. To make the radar antenna smaller, higher frequencies must be used. Military MW radar, which typically operates at 94 GHz, requires much smaller antennas, allowing integration of radar antenna without compromising automotive styling. However, with the increase in operating frequency comes an associated increase in cost. To make radar cost effective, the waveguides and related parts associated with conventional 94 GHz MW radar must be replaced with a one or two piece chip set. These chips are fabricated from Gallium Arsenide (GaAs), and compared to Silicon, are more expensive to manufacture. For comparison, cellular phones typically operate at 1-3 GHz, and make extensive use of GaAs. Despite the widespread use of cellular phone technology, GaAs chip sets for this application (at these frequencies) are just beginning to compete in price with Silicon [Costlow, 1994].

At the present time, automotive radar technology lags the IR technology for intelligent cruise control [Martin, 1994] (Leica estimates an OEM cost of their ICC at $125 if purchased “in quantity,” whereas millimeter wave radar is struggling to come in at under $200 [Costlow, 1994]). However, for applications more involved than ICC, millimeter wave radar systems show greater potential than do IR systems.

III. MIMIC Radar Technology

Inexpensive MW radar will be realized if the expensive components such as waveguides and signal processing hardware can be replaced with a one or two piece chip set; this is the thrust of ARPA's MIMIC program. The most cost effective configuration integrates transmitter, receiver, and signal processor onto integrated circuits. Defense applications such as smart weapons require small, rugged, low power, accurate devices capable of identifying a target and tracking it until interception and destruction. Requirements for these devices include reliable operation from -25°F to 145°F, operation under shock and vibration loading to 18,000 G's, small size, and low power drain. Sensors which can operate under these conditions should be operative under even the harshest conditions that highway going trucks typically encounter.

A number of radar manufacturers participated in the ARPA MIMIC program; Alliant Techsystems (ATK), Hopkins, MN, is currently associated with two of three Phase 2 MIMIC programs. Millitech, South Deerfield, MA, has 5 years experience with automotive radar, and has developed prototype systems for European automobile manufacturers. Currently, Millitech is working with Ford Motor Company to develop ICC. Millitech has not participated in the ARPA Demo II autonomous vehicle program to date; however, TACOM, the U.S. Army's Tank Automotive Command, recently contacted Millitech regarding Millitech's participation in future technology demonstrations. VORAD currently markets a radar based collision warning system for heavy trucks and buses.

Overviews of collision avoidance technologies (including radar systems) and countermeasures are provided in [Fancher, 1994] and [Najm, 1994]. However, detailed technical information concerning millimeter wave radar remains secret or proprietary. The following analysis is based on information provided by ATK, Millitech, and VORAD. Technologies available for both forward looking and vehicle periphery radar are examined; a brief summary comparing these three systems is provided in Table 1 on page 18.

Forward looking radar. For forward looking radar, the ATK system provides for operation at 94 GHz, and provides the following outputs: range to obstacle, range rate (relative velocity) to obstacle, range profile of obstacle, and radiometer. Range profile uses a monopulse High Range Resolution (HRR) technique to determine a radar "signature" of the detected obstacle. The Radiometer measurement determines the intensity of the returned signal, which can be used to determine the material from which the obstacle is constructed. Application of the HRR and radiometer data provides a means to determine whether the obstacle is automotive, flora, fauna, etc. Knowledge of the obstacle can be used to predict the trajectory of the obstacle, thereby increasing the probability that a collision avoidance maneuver will be properly executed.

This radar system uses an electronically scanned microstrip planar/conformal antenna. Electronically scanned antennae allow the target to be tracked by configuring the array electronically in real time, and avoid the problems associated with mechanically moving radar antennae. Recall the problem with the Leica ICC system; as vehicles traversed corners, the system would lose "lock" because the IR beam only looked straight ahead. A phase arrayed antenna can be steered electronically in order for the signal beam to track the vehicle around corners, over hills, etc., without the need for complex mechanical linkages or servo systems. Moreover, the use of a microstrip antenna allows the antenna to be "molded" to conform to the shape of the device in which it is installed. In the case of highway vehicles, the antenna could be integrated into the grill, the bumpers, or the body of the car, simplifying the job of the vehicle designer.

ATK could supply forward looking radar with an output of the order of 100 mW which would yield a maximum range from 1 to 1.5 km, and a range resolution from 0.2 to 0.5 m. Beam widths for such a radar are typically rectangular, and the beams could range in size from 2° x 4° to 6° x 12°. An antenna for such a system would be from 5 in. to 8 in. in diameter with a depth on the order of 0.4-0.8 in. Such a radar system could process sensor information at rates beyond 1 KHz.

Millitech offers two systems for automotive use: a three beam forward looking radar and a scanning system similar to the steerable ATK system described above. Because the available technical details for the Millitech scanning system are similar to those provided by ATK for their steerable array system, further description of the Millitech scanning system are not be provided here. The three beam system [Milli, 1994] has been developed for front looking automotive ICC and driver warning systems. Each beam width is 2° in both elevation and azimuth. This radar operates at 77 GHz as required by the European market. Although military derived hardware has typically used a 94 GHz center frequency, the FCC has recently approved 60 GHz, 77 GHz, 94 GHz, and 140 GHz for automotive radar use. Millitech's three beam radar provides information on the order of 1 KHz, and measures 145 mm diameter and 75 mm depth.

VORAD offers current production radar for truck use. Maximum Range is on the order of 180 meters with range resolution of 3% of range; range rate measures from 0-160 km/hr, with resolution to 1 km/hr. The beam angle is 4° in azimuth, 5° in elevation. Range and range rate information for up to three obstacles is passed at a rate of 2 Hz [Wixom, 1994]. The applicability of VORAD for automatic collision avoidance systems is suspect because of the low 2 Hz information bandwidth. Range and rate information would have to be provided at higher rates given the maximum range of the VORAD system.

The success of such radar boils down to cost. The estimated OEM cost given by Millitech [Wood, 1994] for the Millitech three beam radar system as described above could be as low as $200 for an annual production rate of 100,000 units, which is certainly competitive with Leica's system, and meets the OEM requirement of prices of less than $200 OEM [Costlow, 1994]. The authors estimate that the price for both the ATK and Millitech electronically steered radar would be approximately 50 - 100% higher for an annual production level of 100,000 units.

Periphery Radar. For highway use, the needs of periphery radar are quite different than those of forward looking radar. For a lane change maneuver on a multiple lane interstate highway, the lane into which the vehicle is to move must be clear both to the side and behind the vehicle. In this situation, the required range of the periphery radar is considerably less than that of the forward looking radar due to the limited closing rates. For this application, ATK is capable of producing an FMCW radar operating between 1 and 10 GHz which integrates MIMIC chip sets and microstrip planar antennae. Radar output power would range from 5 to 20 mW, and sensor information could be processed at rates beyond 1 KHz. Maximum range is on the order of 10 to 30 m, with a range resolution of 0.2 to 0.5 m for radar beam angles from 35° to 55°. Technically appealing from an automotive designer's point of view is that the entire radar system (antenna, MIMIC chip set, and flexible PC board) could fit into a volume less than 1.2 to 1.5 cubic inches. Such a small package will facilitate integration into door panels, fenders, and bumpers, leading to a "smart skin" for highway vehicles. At a production rate of 100,000 annually, the estimated cost of such a radar package falls into the $10-12 range. VORAD currently markets a side looking obstacle detection gage; the gage indicates whether a vehicle is sensed, but provides no information regarding range, range rate, etc. Millitech did not provide information regarding radar suitable for periphery applications.

Additional investigation will be required to determine the effects of the limited maximum range offered by such systems; a maximum range of 10 to 30 m may prove inadequate for rear looking radar sensing high relative velocities (i.e., cars speeding in the lane to the left). Greater output power (and therefore greater maximum range) may be necessary for automotive applications.

IV. Conclusions and Recommendations

Conclusions. Vehicle radar is quickly becoming a reality; in fact, a commercial radar based driver warning system is presently available to trucking fleets. Initial reports show that driver acceptance is good, and that demand for such systems will increase. Both radar manufacturers and automobile manufacturers are developing radar for truck and passenger car use. Because radar reliability, ruggedness, and size requirements for military use match well with the requirements for road going vehicles, defense companies are adapting military based radar in an attempt to find commercial markets for their products. The FCC has also recognized the reality of automotive radar, and has established 4 frequencies (60, 76, 94, and 140 GHz) for its use.

With the advent of automotive radar, both states and the Federal Government will have to enact and enforce regulatory legislation for automotive radar. To do so, the performance capabilities of automotive radar systems will need to be established, and existing and potential problems will need to be addressed and documented. Vehicles equipped with various radar based systems have the potential to interact with other vehicles in ways yet unknown. For instance, airbags affect only those passengers in a vehicle so equipped; however, radar based ICC affects the vehicle so equipped *and* vehicles ahead, to the sides, and to the rear. A complete understanding of these emerging technologies is required before approval for use on public roads is granted. To put Mn/DOT in a position to better understand the ramifications of vehicle radar and create the proper public policy towards radar based vehicle control systems, the following recommendations are made.

Recommendations. Our goals under this contract were to perform a baseline evaluation of the MIMIC technology. This has been completed. A more rigorous evaluation will require testing of hardware under a variety of operating conditions. In order to do so, technical support from ATK will be required at a cost $30,000; this price does not include University personnel required to perform the evaluation or the cost of materials and equipment required to support the evaluation. Because the sensors to be evaluated were developed for military use, approval for the evaluation will be required from ARPA. With the availability of funds, we would intend to perform hardware evaluations of systems from Millitech, VORAD, and ATK. Information and preliminary plans are found below.

Conversations with Millitech have proved fruitful. First, Millitech developed their scanning and three beam sensor technology independent of ARPA funding, and therefore can release technology without outside approval. Second, Millitech can lease both the three beam and scanning radar systems for evaluation by the University. A copy of the quotation from Millitech can be found in appendix A.

Discussions have also been held with VORAD, and our evaluation plan has been discussed with Kevin Wixom, Director of Engineering at VORAD, San Diego, CA. VORAD can supply a radar system which will provide range and range rate data for up to three obstacles located in the radar beam nearest to the vehicle [Wixom, 1994]. The evaluation system is based on current production units, and would be modified to interface with our vehicle control computer. Cost of the system is approximately $3,000. If a significant amount of additional technical support would be required, VORAD would charge on an hourly basis.

The ATK MIMIC technology is also to be evaluated. The time frame for such an evaluation is at present unknown because of the need for ARPA approval. Moreover, the evaluation cost for the steered array technology has yet to be established. The evaluation plan for ATK's MIMIC technology includes a study of both the steered array radar and the periphery radar if timing and cost issues can be resolved.

Our MIMIC technology evaluation plan serves two purposes: first, it allows us to evaluate the physical characteristics of a variety of radar systems; second, armed with these physical characteristics, mathematical models of sufficient fidelity may be developed. Radar sensor evaluations will include determination of maximum and minimum range, maximum and minimum range rate, range and range rate maximum error, range and range rate resolution, beam width(s), angular resolution, true information bandwidth, and the effects of rain, sleet, snow, heat, vibration, and shock. This evaluation will provide "hard" sensor data which can be incorporated into the sensor model. The sensor model can then be incorporated into radar based vehicle warning and control system simulations, which will provide preliminary information regarding the performance potential of the actual systems. This information will provide Mn/DOT with information regarding what benefits and potential problems to both safety and traffic flow the introduction of such systems will bring to highway transportation in the state.

The simulation environment will be used to study the effect of sensor placement on vehicles, to determine the number of sensors required to ensure adequate vehicle coverage, and to evaluate how different collision avoidance systems (including differences in sensor locations, sensor type, and number of sensors per vehicle) will interact in a highway environment. Vehicle interaction is a concern because of the potential for dynamic instability between vehicles when both are equipped with different collision avoidance strategies. For example, one system may be designed to maintain close headway, whereas another system may be designed to maintain a greater gap. Without a stable equilibrium, these vehicles may continually oscillate in an attempt to maintain the proper distance. This continuous oscillation may distract other drivers or upset vehicle occupants, which in turn could lead to poor driver acceptance of such systems. Another problem may be the attenuation of the radar signal by other devices. Global Marketing Associates have begun to market a device called the "Blackout" which absorbs the radar signals from police radar guns, rendering the police radar gun completely ineffective [Stereo, 1994] (police radars read 0 mph). The device is claimed to be legal under paragraph 15 of the FCC regulations. Such devices could wreak havoc with any radar based vehicle control systems, and need to be investigated further.

After the testing of the radar hardware to determine physical characteristics and appropriate mathematical models comes the integration and testing of the radar system as one component in a collision avoidance system. Although the integration of the radar system into a collision avoidance system is beyond the scope of the recommendations made here, such work has been considered and presented in [CRASH, 1994]. The work proposed in [CRASH, 1994] will use radar extensively for collision avoidance behaviors including lane changing, merging, and braking.

Comparison of Automotive Radar Proposed for Hardware Evaluation

Manufacturer	Center Freq.	Max. Range	Number of Beams	Azimuth	Elevation	Antenna Size
Alliant Techsystems	94 GHz	1-1.5 km	one steerable	2°-6°	6°-12°	125-200 mm dia 10-20 mm deep
Millitech Corporation	77 GHz	150 m	3	2°	2°	145 mm dia 75 mm deep
VORAD Incorporated	24.7GHz	180 m	1	4°	5°	8.1 in x 6.7 in x 5.1 in

Table 1

IV. References

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