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**FEASIBILITY OF AN ANTICIPATORY NONCONTACT PRECRASH
RESTRAINT ACTUATION SYSTEM***

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Feasibility of an anticipatory noncontact precrash restraint actuation system

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ABSTRACT

The problem of providing an electronic warning of an impending crash to a precrash restraint system a fraction of a second before physical contact differs from more widely explored problems, such as providing several seconds of crash warning to a driver. One approach to precrash restraint sensing is to apply anticipatory system theory. This consists of nested simplified models of the system to be controlled and of the system's environment. It requires sensory information to describe the "current state" of the system and the environment. The models use the sensory data to make a faster-than-real-time prediction about the near future.

Anticipation theory is well founded but rarely used. A major problem is to extract real-time current-state information from inexpensive sensors. Providing current-state information to the nested models is the weakest element of the system. Therefore, sensors and real-time processing of sensor signals command the most attention in an assessment of system feasibility.

This paper describes problem definition, potential "showstoppers," and ways to overcome them. It includes experiments showing that inexpensive radar is a practical sensing element. It considers fast and inexpensive algorithms to extract information from sensor data.

Keywords: anticipatory systems, airbag sensors, precrash restraint, advanced vehicle control systems, chirped wavelets, automotive radar, crashworthiness, real-time signal processing, multirate analysis

1. PROBLEM STATEMENT

The ultimate goal of this project is the development of a sensory system that predicts with great accuracy, based on its knowledge to the present moment, whether or not it is about to become the victim of a crash. The prediction includes an estimate of the energy and direction of the crash. The vehicle will have a suite of restraint devices, driver and passenger airbags, side stiffeners in the right and left doors, and possibly other devices, each of which allows for a range of degrees of deployment. It is not desirable to fully deploy all restraint devices for every crash, and a context-sensitive decision must be made as to which devices to deploy and to what degree.

An anticipatory sensor can do this; an accelerometer-based sensor cannot. The accelerometer indicates two things: whether or not a crash is already in progress and, if so, the severity of the crash. This is a purely reactive system. It knows nothing until the crash actually starts. The information it provides to the restraint system requires that the restraint system deal with a situation that is already occurring. For many types of crashes, there is not sufficient time to determine that a crash is already in progress, decide what to deploy, and complete the deployment before the crash energy is transmitted to the occupants of the vehicle. To obtain the necessary extra milliseconds, what is needed is an anticipatory system.

This paper covers only the feasibility study phase of an anticipatory sensory system. The objective of any feasibility study is to answer the question, "Can the thing being studied really be done?" A reasonable way to answer the question for this case is to determine whether or not there are "showstoppers" that might preclude the implementation of an anticipatory sensory system for the proper deployment of precrash restraints.

For practical deployment in a vehicle, the anticipatory system must meet several constraints. Since the predictions pertain to the state of affairs ~100 ms in the future, the process of converting sensor data into a prediction has to happen in much less than 100 ms. The error rate (false positive and false negative) must be extremely low. Finally, the whole system

must have a reasonable potential to be producible for a few tens of dollars per copy when produced in quantities of several million.

It is tempting to consider the arming function to the exclusion of the firing function. Arming requires information about target dynamics, which can be obtained from radar returns. It does not require target class or mass.¹ The consequences of error may be tolerable. A false positive means that the system arms but no crash occurs. If a crash does not occur within some prescribed amount of time after arming, the system can disarm, probably with no harm done. A false negative means that a crash occurs, but the system does not arm until forced to do so by the crash detection accelerometers; in that instance, the advantages of the anticipation are lost. Swihart and Lawrence have produced experimental data that show at least a 10% reduction in firing time for accelerometers supplemented by radar-based crash prediction for arming.²

The firing function is costlier and riskier but leads to a greater potential payoff than the arming function. In addition to target dynamics, the firing function requires information about target class and mass. It has not been proven that class and mass data are obtainable by a device that must meet the constraints of an automotive precrash restraint sensory system, nor was it an objective of this study to explore the question. The consequences of error are quite severe for an anticipatory firing system. A false positive is very likely to cause a crash where none would have occurred otherwise. A false negative might cause the restraint to fail to actuate during a crash, causing more severe injury (or loss of life) than would have otherwise occurred. The payoff for an anticipatory firing system is that it would deploy the restraint device several tens of milliseconds faster than a contact-based firing system.

Before practical development of such a sensor goes forward, the choice must be made between these two functionalities. If the sensory system's predictions are to be used only to arm the restraint system, then the risk is relatively low, but the payoff is marginal. If the sensory system's predictions are to be used to actually deploy the restraint system, then the prospect of payoff is relatively high, but the consequences of error are severe.

2. BACKGROUND

Research sponsored by the National Highway Traffic Safety Administration (NHTSA) in predictive crash sensing goes back to the work in the early 1970s by Holstrom and associates.³ These researchers defined active restraints as devices requiring some action on the part of the vehicle occupant, such as seatbelts, and defined passive restraints as devices not requiring action by the vehicle occupants, such as airbags. Their report uses "anticipatory" to mean "precrash"; it does not describe a formal anticipatory system.

They recommended a hybrid system. They asserted that accelerometer-type actuators are adequate below 30 mph but that precrash warning is needed at higher speeds and suggested a system with both accelerometers and microwave radar. Below 30 mph, only the accelerometers would be used, in conventional fashion, and the radar would not operate. Above 30 mph, the radar would provide advance warning, and the accelerometers operating at a low threshold would provide confirmation. In the 30- to 60-mph range, they did not recommend making a decision to deploy based solely on radar data.

Holstrom and associates³ did not prescribe an acceptable false alarm rate but speculated that it should fall in the range from one occurrence in 4 years (probability of accident involvement) to one occurrence in 2500 years (probability of fatal injury). Their rates of occurrence were based on statistics for the early 1970s. Statistics for 1990 result in averages of one police-reported crash involvement per 14.8 years of driving and one fatal crash involvement in 2910 years of driving.⁴

More recent literature changes the adjective from "anticipatory" to "predictive," but the emphasis is still on the sensing hardware element and not the processing. It does not discuss formal anticipatory systems. Swihart and Lawrence² are concerned with the same result as the early NHTSA work: precontact warning of an impending crash. Their application is more demanding, requiring information for context-sensitive deployment. Their system would use radar-based prediction to perform the arming function and not the firing function. Their experimental data show at least a 10% reduction in firing time for accelerometers supplemented by radar-based crash prediction for arming. They assert that a system that fires an airbag solely on the basis of a noncontact prediction requires not only much better target dynamics than their system provides but also the class (type and/or mass) of vehicle.

Many different sensor technologies have been explored for crash-avoidance sensing. A systematic comparative survey of these technologies was performed by Najm.⁵ His emphasis was on the sensor technology rather than on the signal processing details. He notes that filtering or gating of radar returns is used to provide an estimate of target dynamics. Useful dynamical information does appear to be present in practical radars; and good, fast, cheap signal processing should do a better job of extracting it than is being done by present commercial devices.

While the recent literature on crash warning provides insights into the capabilities and limitations of radar, it does not provide (nor was it intended to provide) much guidance of the processing side of the precrash restraint problem.⁶ For example, a vehicle control system investigated by Ozguner et al.⁷ uses a good radar-reflecting target as an integral element of the overall system. Helpful exceptions include the work of Fujita, Akuzawa, and Sato⁸ and Najm, Mironer, and Fraser;⁹ both of these studies provide insight into the extraction of target dynamics from sensor data.

An unresolved engineering problem in having the vehicle sense its own dynamical state is the determination of the minimal set of precrash information actually required by the system model and the signal processing task of extracting it from the output of existing on-vehicle sensors. This problem appears to be straightforward, and its solution does not seem to require any new conceptual breakthroughs.

The element that the precrash restraint actuation sensor has in common with the other crash-predicting technologies is the element used to sense the environment. Almost all propose using microwave radar. Infrared proximity detection works for robot guidance but only in low-speed indoor situations.⁹ The same has been demonstrated for ultrasonic sonar.¹⁰

3. ANTICIPATION

A formal anticipatory system is based on mathematically formalized principles of anticipation. The term generalizes the notion that the system can take present action based on an expectation of a future state. It refers to a system in which decisions are made by an algorithm that emulates the anticipation process found at a primitive level of biological intelligence. The principles of anticipatory systems were rigorously derived by Robert Rosen, a mathematical biologist.¹¹

The most important use of the anticipation mechanism in nature is to preserve the safety of the creature doing the anticipating. Based on an extremely sparse set of percepts describing the present state, a creature performs the remarkable feat of recognizing, with sufficient time to take corrective action, whether or not the future state constitutes a danger. Since eons of natural selection have caused the anticipation mechanism to abound in nature, not only must it be effective, but also it must have superior survival value compared to other paradigms for identifying threats.

The anticipation process is conceptually well founded. Anticipation is one of the most primitive functions of biological intelligence. Unlike higher cognitive functions, it is deterministic. It does not require that the creature doing the anticipating make a volitional choice to do so. Being deterministic, the rigorous development of a theoretical foundation for a mathematical description of anticipation is straightforward, albeit tedious.

If we learned how to perform the seemingly impossible task of heavier-than-air flight by observing how it was done in nature, does it not make sense to try the same thing in the development of robust safety systems? This was precisely the approach taken by Tsoukalas in the development of anticipatory controls for large systems such as nuclear power plants.¹²

The implementation of a formal anticipatory system in a small instrument has never been reported in the literature. The most likely reason for this is that, before the recent development of high-performance processors and algorithms, it was probably impractical. However, as this feasibility study indicates, at the present level of technology, the development of an anticipation engine in a small system is the next logical step in the progression. It is reasonable to expect that the development of an anticipatory system applied to vehicular safety should lead to a high payoff in reduction of accidental death and injury.

An anticipatory system is a formal mathematical scheme based on interacting predictive models, as shown in Fig. 1. One model takes information about the past and present state of the vehicle and makes a prediction of its dynamical state in the near future. Another model takes information about the past and present state of the environment (i.e., likely targets) and predicts the dynamical state of the targets in the near future. Based on these sets of predictions, the system develops its prediction about the impending crash.

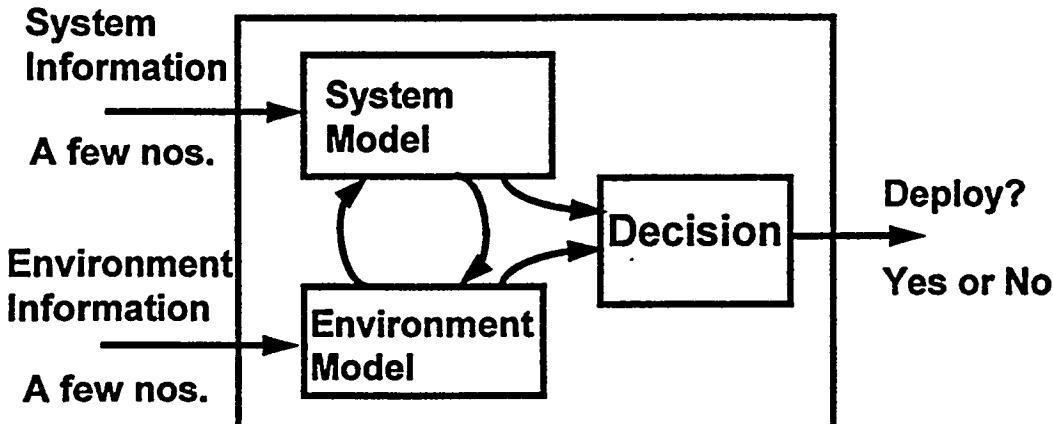


Fig. 1. Anticipatory system.

For a model to operate, it needs real-time data streams to provide the "present-state" information on the vehicle and the targets. This requires a suite of sensing transducers that provides "data" and real-time signal processing that extracts "information" from the data. Thus the anticipatory system is not a sensor with some

incidental built-in intelligence. Rather, it is an integrated intelligent system that incidentally uses an array of sensing elements, signal processors, and an anticipation engine.

The major unsolved problem is the algorithm, not the hardware. Specific questions are as follows: Can a formal anticipatory system consisting of interacting nested models reliably predict the onset and severity of a crash? What are the computationally cheapest models that provide an adequate prediction? What input information does the system model need, and how sparse can the information be without significantly diminishing the performance of the system model? What input information does the environment model require? Do the output data of available sensor elements contain the information needed by the models? What are the computationally cheapest signal processing methods for extracting the information needed by the models from the data produced by the sensors?

The dynamical models for crash prediction are based on deterministic classical physics. The development of the specific models themselves would be tedious but straightforward. The models should be implementable in no more than a few thousand machine language instructions. Given present-day microprocessor clock rates, it should be possible to transform the initial dynamical conditions into a prediction in less than a millisecond.

Rosen¹¹ identifies five necessary attributes that distinguish an anticipatory system. The first is that an anticipatory system, S_2 , must contain a model, M , of another system, S_1 . Second, the anticipatory system, S_2 , contains a set of observable quantities that can be linked mathematically to S_1 and an orthogonal set of observables that cannot. Third, the predictions of the model, M , can cause an observable change in the state of S_2 . Fourth, there must be some observable difference in the interaction between S_1 and S_2 when the model is present and when the model is not. Finally, M must be a predictive model; based on the present conditions, M must change state faster than S_1 (operate faster than real time) such that M 's changed state constitutes a prediction about S_1 .

Since the vehicle and its environment (the set of objects into which the vehicle might crash) are everyday-sized objects moving at ordinary speeds, the equations of classical dynamics should provide an adequate model.

$$\frac{dx_i}{dt} = f_i(x_1, \dots, x_n), \quad i = 1, \dots, n$$

$$\frac{dy_j}{dt} = g_j(y_1, \dots, y_m), \quad j = 1, \dots, m$$

Here the vector x_i characterizes the state of the vehicle at an instant, and the vector dx_i/dt characterizes the time rate of change of the state of the vehicle at an instant, where the state has i degrees of freedom, and f_i is a mapping function that is not necessarily linear and not necessarily conservative. The vector y_j characterizes the state of the environment at an instant, and the vector dy_j/dt characterizes the time rate of change of the state of the environment at an instant, where the state has j degrees of freedom, and g_j is a mapping function that is not necessarily linear and not necessarily conservative.

Since they must operate faster than real time, neither model is an exact characterization of the system it describes. A major task of a subsequent phase of the development of a practical air bag actuation sensor is to determine the minimal set of vectors x_i and y_j that account for the necessary observables and the functions f_i and g_j that adequately characterize the system for this particular application.

How these models and the interaction between them are to be implemented in the sensory system hardware is a computational detail. One promising method would be to implement the two dynamical models as two different cellular automata, each on its own set of simple dedicated massively parallel very large scale integrated circuit hardware. (Note: A cellular automaton is a replacement rule that forces the next state of a cell to be a function of its current state and neighbors.) The interaction between them could be modeled as fuzzy set membership; there already exists a dedicated fuzzy logic chip that is probably suitable to the task. (Note: Fuzzy set membership is a mathematical measure of the degree to which an object is a member of a set.) However, this example illustrates only one possible method. Others might turn out to be faster, better, or less expensive.

Sensing the state of the vehicle and extracting the information from the sensor data should not be a showstopper. On-vehicle sensors for velocity, acceleration, strain, etc., represent a mature technology; and processing can be done in real time with cheap, dedicated digital signal processing (DSP) chips. In fact, it is the abundance of inexpensive sensor data describing the state of the vehicle that defines the engineering problem for this part of the system. How sparse can the data set be made to still provide an adequate description?

If there is a showstopper, it is in developing the information about the state of the environment. Optical techniques are not practical; they are too easily disrupted by environmental effects. Radio-frequency (RF) radar offers the proper range and resolution but historically has been extremely expensive and has required absurdly fast processing times. If RF radar is used in an impending crash detector, are there ways of implementing it within the cost constraints of consumer electronics? Does RF radar generate the information that the environment model needs? Can target dynamics be extracted from the data fast enough for it to be practical? Can target class be extracted at all?

To show that the anticipatory airbag sensing system is feasible, the experimental and analytical research effort in this project has concentrated on extracting information on target dynamics from the output data of cheap sensors. This project does not confuse the system with its transducers; the global objective remains the development of an anticipatory system. Rather, the feasibility study focused its primary effort on analysis of environment transducer outputs because uncertainty about the availability of environment information constitutes the most likely barrier to practical development.

4. EXPERIMENT

Because of budget limitations, the only experimentation of any consequence was done with a surplus burglar alarm radar unit purchased from an amateur radio supplier for \$20. This was a Doppler radar that puts out 10 mW at 10 GHz. It uses a Gunn diode both as the transmitter oscillator and as the receiving local oscillator and a hot carrier diode as a mixer. A horn antenna is used with the radar; its beam width is 23° in azimuth and 21° in elevation, and it has a gain of 16.6 dB.

Doppler radar experiments were performed with three vehicles, a Ford Econoline van; a small cart with a flat, adjustable reflecting screen; and a passenger sedan. The experimental geometries are shown in Fig. 2.

The experiments were conducted with the radar antenna 3 ft above the ground. In the head-on experiments, the vehicle was run directly toward the antenna. The vehicle was 50 ft away at the start of the run and 5 ft away at the end of the run. In the side-swipe and pass-by geometries, the radar was positioned back from the edge of the roadway, and the

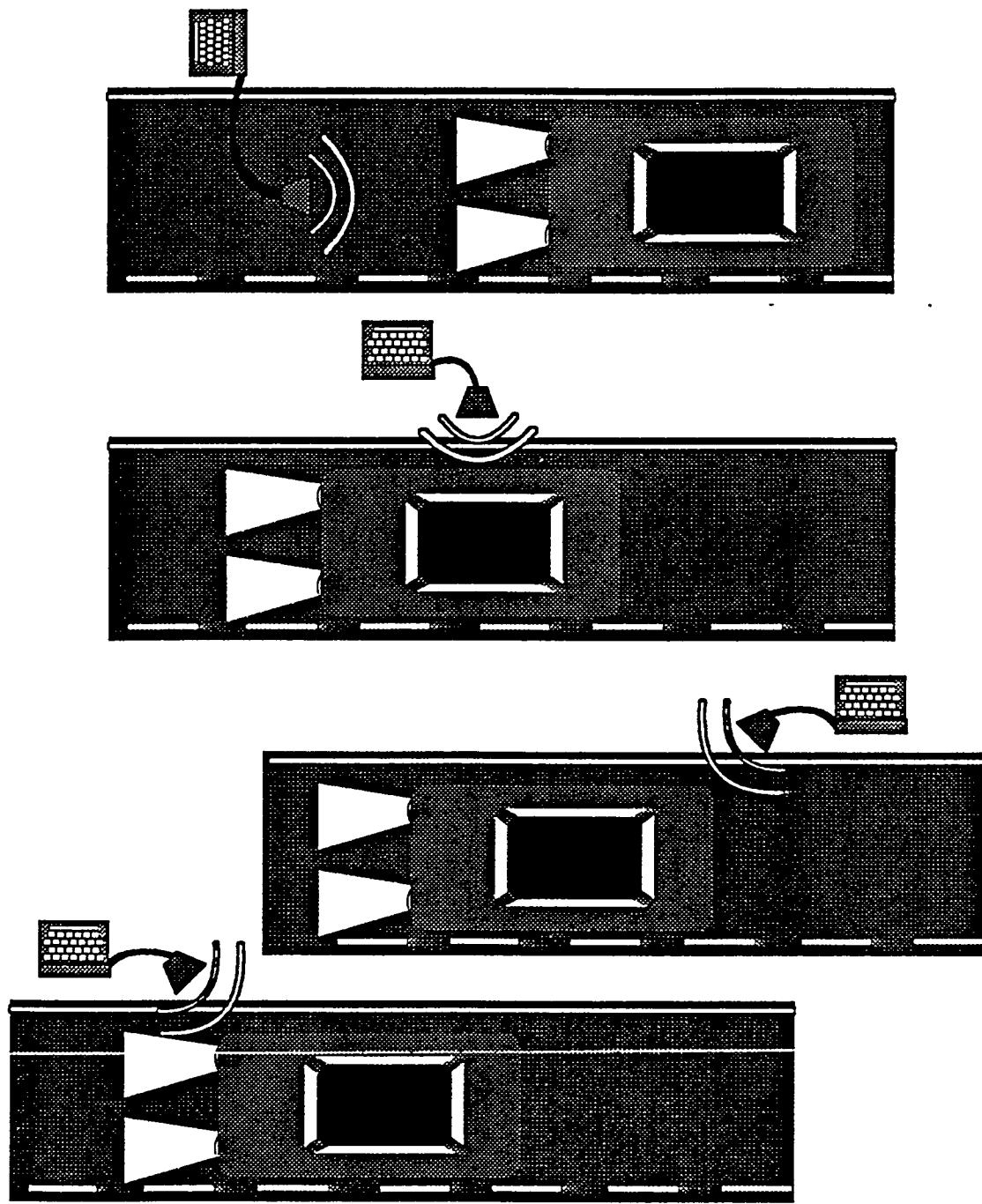


Fig. 2. Experimental geometries.

perpendicular distance from the antenna to the side of the vehicle was 12 ft at nearest approach. Some of the tests were conducted in light rain and snow. Doppler radar returns were not affected by weather effects.

The objective of these experiments was proof of principle. Can we establish that the radar returns really contain the information needed to feed the environment model? The experiments were not conducted with the exhaustiveness or the precision needed to establish engineering specifications.

The only independent check of target dynamics was provided by a set of two wheel-actuated switches. These provide an accurate measure of average target velocity in the time interval during which the front wheel of the target passes between the two switches. Data describing the profile of velocity as a function of time were not collected. In a course of experiments to establish engineering specifications for a practical sensor (as opposed to proof of principle, as was done here), the velocity profile should be collected.

The duration of each signature was 2 to 4 s. A sampling rate of 1000 samples per second was used for digitizing. A typical Doppler signature has 2000 to 4000 samples.

What the Doppler experiments yielded were sets of time series data whose modulation corresponds to the instantaneous velocity of real-world targets, collected under real-world conditions with cheap hardware. The major result of these experiments is that a good estimate of real-time acceleration can be obtained. The implication is that with a system (such as pulsed radar) that also provides displacement, it should be possible to obtain good estimates of acceleration, displacement, and velocity. Our experiments did not yield information on angle of approach.

5. ANALYSIS

After the experiment, analysis was performed to determine whether or not the observed signatures contain useful information. One way to examine a signal for its information content is the Karhunen-Loeve Transform (KLT) (Ref. 13, pp. 25-30). The KLT is the optimal transform for detecting information buried in a signal; however, it is impractical to implement in real time.

The KLT is impractical as an information extractor in an anticipation engine. What it can do is to establish principle. If the information is there, the KLT will find it. For example, if KLT analysis demonstrates that both velocity and acceleration information is extractable from a Doppler signature, then the engineering task of developing an information extractor degenerates to the job of finding a computationally cheap transform that approximates KLT performance in extracting these two features but discards everything else.

The KLT amounts to using the principal eigenvectors of the covariance matrix as a basis to represent the process. There are (physically) three dimensions to the state space of a Doppler chirp. (Note: The Doppler chirp is the frequency modulated pattern returned by a Doppler radar.) Application of the KLT can be appreciated by comparing Figs. 3, 4, and 5.

Figure 3 is the time domain plot of the last 750 ms of the slowing-down event for the van. There are three separate regions identifiable as to amplitude. A likely reason for the amplitude variation is that different portions of the van, having different reflectivities, are being viewed by the receiver as the van approaches. These regions are quite evident in the plot.

If we now form a time-delay matrix consisting of

$$\begin{aligned} A = & \quad a_1, a_2, \dots, a_m \\ & \quad a_2, a_3, \dots, a_{m+1} \\ & \quad \dots \dots \dots \end{aligned}$$

we create a square, positive definite matrix of dimensions m by m from A multiplying it by its transpose. The eigenvalues are found, and the first three are used to reconstruct the signal in phase space. The optimum value for m is determined by taking the ratio of the first two eigenvalues; when they are approximately equal, we have spread out the signal to a maximum extent (we assume that the dominate process is a simple sine oscillation).

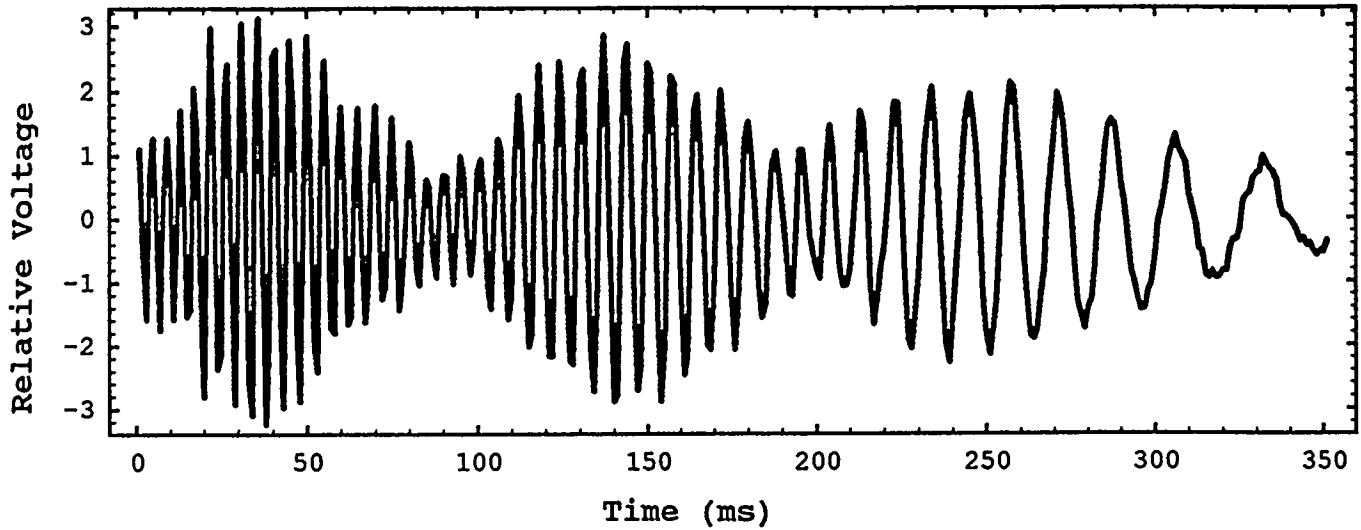


Fig 3. Doppler signature with possible multiple reflections.

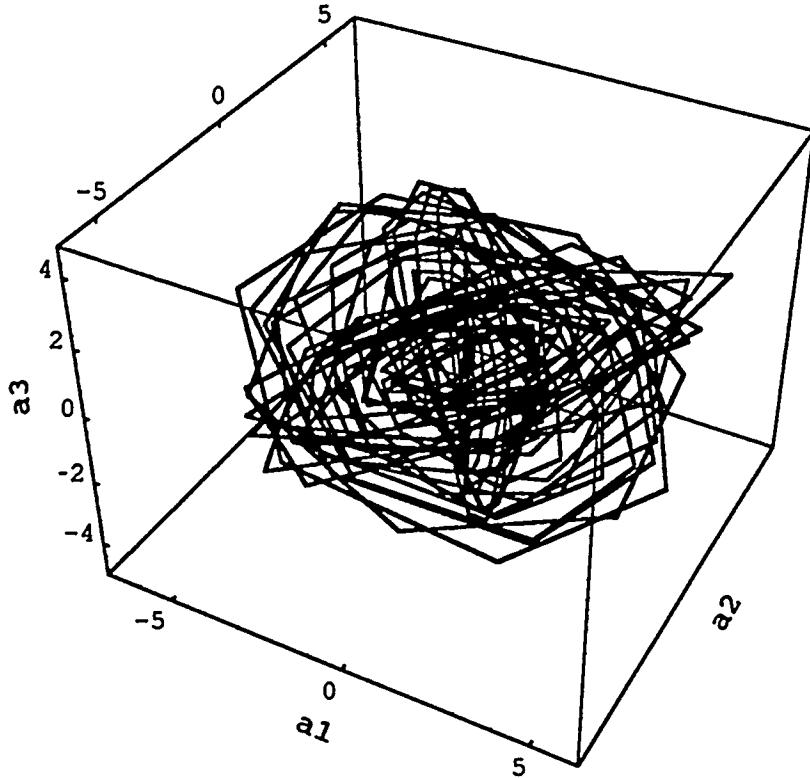


Fig. 4. Projection onto first three eigenvectors.

The KLT analysis shows that the information is there but is too costly to use as a practical system. There are cheaper analysis methods that approach the information-extracting power of the KLT. In this application, chirped wavelet analysis appears to be the most promising method.

The result of analyzing the above signal in this fashion is shown in Fig. 4. First, we show the eigenvalues for $m = 9$. This value of m spreads out the fundamental oscillation equally along the first two directions.

If we use the first three eigenvectors as a basis for the phase space, we obtain the plot in Fig. 4 using all 350 data points. Note that there are three disks, each tilted with respect to each other. The three almost-planar trajectories roughly correspond to the three regions in the data set.

We can now look more closely at the event in the same phase space by considering only 50 events at a time, resulting in six regions over the 350-point data set. These plots are shown in Fig. 5, where the first 50-point region is shown in the upper left and the last, in the lower right.

Note that all but the first are nearly two-dimensional trajectories. The first one clearly shows the presence of acceleration during the entire 50 time steps by the helical structure. The last trajectory is as decidedly different an orientation than the previous four.

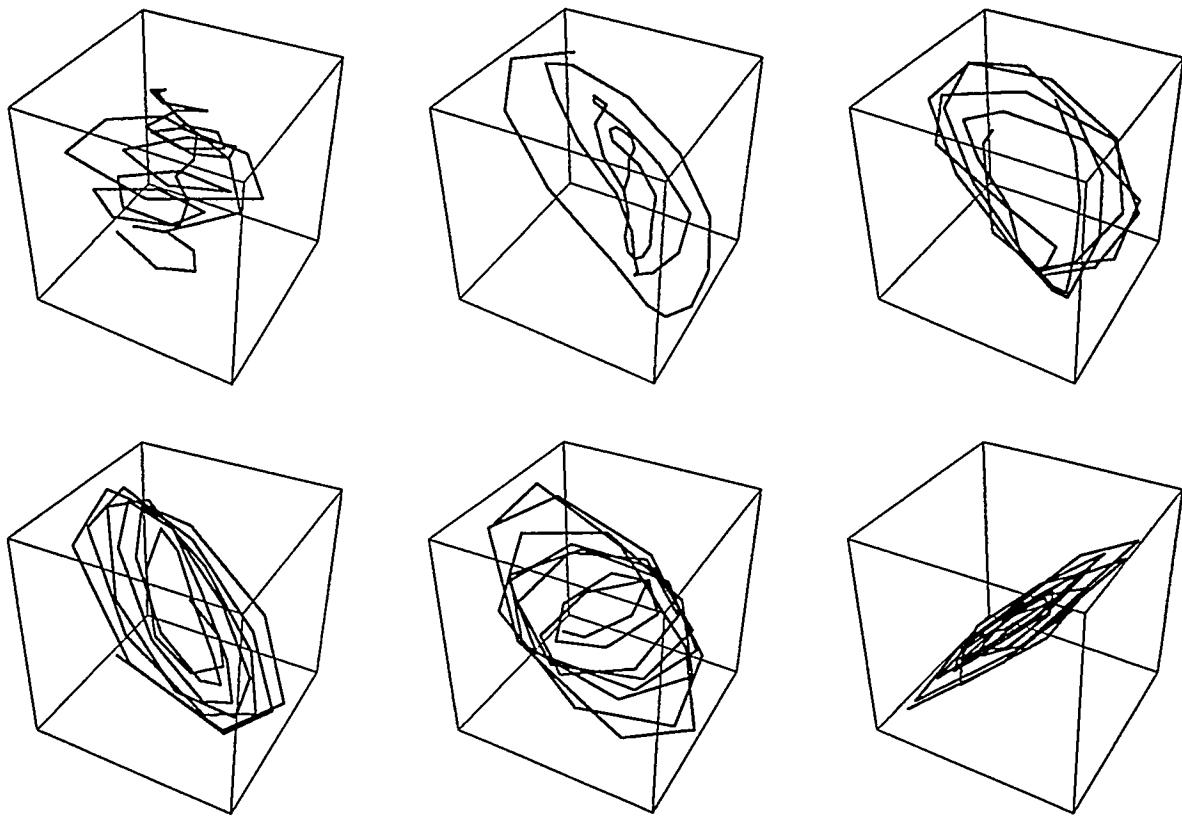


Fig. 5. Resolution of projection into distinct surfaces.

Chirplet analysis uses a number of chirp wavelets, each with a different deceleration (linear frequency behavior).¹⁴ The Fourier transform (FT) of such a set convolved with the FT of data segments picks out the appropriate components, identifying regions as to both acceleration and velocity.

Each data section, each perhaps 100 ms in duration, will require a fast FT (of the data) and a convolution with each of several chirplets (of various linear frequency variations) at each of several scales (corresponding to basic frequency or velocity). The wavelet with the largest correlation is presumed to be the best description of the data. An alternative is to convolve segmented portions of the Doppler signal with a set of filters, each representing a particular velocity and acceleration. If this set is arranged in a hierarchical manner, processing time can be greatly reduced.

The concept of chirplet analysis is that of a bank of matched wavelet-packet filters chosen to span the Doppler signals anticipated. To illustrate the concept, we constructed a set of chirp functions in the frequency range corresponding to five velocities between 5 and 25 mph and five accelerations for each velocity ranging from -10 mph/s to $+10 \text{ mph/s}$. Only one generic set is shown in Fig. 6.

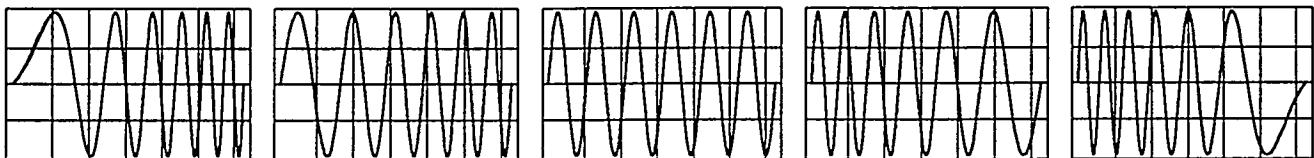


Fig. 6. One row of the chirplets set.

6. BEAMFORMING

Beamforming is a multireceiver variation of the time-domain pulse method that builds up a picture in distance-angle-velocity space. This method has several advantages over the simple Doppler and time-of-flight methods. Conventional methods cannot provide an indication of bearing—the angle of the target with respect to the base vehicle. Thus, we are able to get velocity and acceleration from the Doppler radar, and if we time the pulses, we also get the critical distance parameter. However, with a single transceiver, there is no sure way to identify the bearing of the target.

In addition to being a crucial input datum to the environment model, the advantage of knowing the bearings of a collection of targets is that we may safely ignore any target whose angle changes from one pulse to the next: The only possible collision candidates are those targets whose bearing remains constant over several measurements. This ability to prefilter the space of all possible targets will greatly aid the next processing stages and reduce the computational burden at all later stages. Note that if we are moving, all stationary objects are removed from consideration by the constant-bearing criterion. Considering only the constant-bearing targets, we next ask which of those are moving toward our vehicle at a speed greater than a predetermined (damage-capable) amount. These are the only targets that the anticipatory subsystem need consider in its predictive model.

7. CONCLUSIONS

An anticipatory precrash restraint sensor for the arming function appears to be feasible but is not yet developed. A system based on formal anticipatory principles should produce significantly fewer errors than do conventional technologies. The information needed to determine the dynamical state of the vehicle should be available from the suite of on-board sensors already installed for other functions. The information needed to determine the dynamical state of the target includes displacement, velocity, and acceleration, all of which are extractable from the returns of inexpensive radar. For the arming function, the missing piece in the target dynamics is inexpensive determination of the bearing of the target.

This study found that inexpensive radar in a “real-world” setting does return useful data on target acceleration. The principle has been proven with a \$20 Doppler radar. The velocity and acceleration of the target can easily be extracted from the Doppler radar signal by any of several methods that are implementable in real time.

While Doppler radar proves the principle that dynamical information is buried in the returns of cheap radar, it does not provide displacement information. Displacement information is necessary to feed the environment model of an anticipation engine. Frequency modulated continuous wave or pulsed broadband radar both appear to be workable alternatives. Each is able to provide displacement, velocity, and acceleration data for multiple targets. The makers of both claim that their technology can be mass-produced for a few tens of dollars per copy.

The data produced by a radar system can be converted to target dynamical information by good, fast, and inexpensive signal processing techniques. While the KLT is computationally too costly for use in a small, real-time instrument, it is the best available algorithm for revealing the information buried in a signal. The KLT of the Doppler radar time series appears to simultaneously resolve velocity and acceleration of multiple surfaces. It demonstrates that, in principle, all this information is extractable. What remains is the engineering task of finding a computationally cheaper algorithm, such as the chirped wavelet, that is almost as good as KLT and can be implemented on inexpensive, real-time hardware.

A major near-term priority that remains to be determined is whether the ultimate objective of this research is to use an anticipatory system to arm, or to fire, a restraint system. There is a risk-reward trade-off to be considered in this decision. The arming function is less expensive, and less sensitive to error, than the firing function, but the firing function has a greater potential payoff. An anticipatory detector for the firing function has not yet been shown to be feasible and depends on an inexpensive method of determining the mass or class of the target.

The next specific research objective is to devise an inexpensive way to determine the bearing of the target. This datum is required for both arming and firing systems. Beamforming with pulsed radar has the potential of providing an inexpensive real-time method of simultaneously producing bearing and a threat-no threat target classification. Data on acceleration, velocity, and displacement can be obtained tangentially to the process at virtually no incremental cost.

8. ACKNOWLEDGMENTS

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