Test Results of an Experimental Autonomous Aircraft Landing System Utilizing a 94 GHz FM-CW Imaging Radar

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Abstract

An expermimental system capable of aiding a pilot during adverse weather landings, primarily dense fog, has been built and tested both on the ground and in flight. The system includes a 94 GHz FM-CW radar as the front-end sensor and a back-end digital signal and image processor for image generation , enhancement, and transformation. The high performance 94 GHz radar utilizes a twisted cassegrain reflector, an external ILO, and an HEMT MIMIC LNA/image-reject mixer front end to overcome the low transmitted power and poor receiver noise qualities of typical W-band radar systems. The back-end processing hardware uses a number of processors in a flexible and reconfigurable pipeline architecture for implementation of a variety of different enhancement algorithms. This paper gives a detailed description of this system and the test results which have been recorded on the ground and in flight. The results indicate that this system has future commercial promise.

1.0 Introduction

Landing aircraft in adverse weather, especially fog, has been a problem since the inception of air travel. The inability of the pilot to see the runway causes delays and cancellations on a daily basis. The possibilty of being able to "see through fog" using active radar imaging techniques has been a research topic for many years. Recent advances in MMW radar technology, and signal and image processing have brought this closer to reality. Lear Astronics Corp. has developed an experimental autonomous landing system based on an active 94 GHz FM-CW imaging radar combined with real-time image processing capability for precisely this application.

Traditional 94 GHz radar systems were limited by low transmitted power and high receiver noise figures. In spite of these limitations, the 94 GHz system is more compact, i.e. highly desirable for applications where space is severely limited. The first system designed by Lear Astronics Corp. [BUI et al., 1991] used a simple homodyne bistatic radar to explore the imaging capability at 3 km range with 100 mW transmitted power. The front-end losses were excessive and we were forced to utilize some novel techniques to extend the range coverage [BUI et al, 1992] . Thus, the original system has been changed to encorporate a twisted cassegrain reflector, an external ILO, and a HEMT LNA/image-reject mixer front-end, which overcome these original problems.

The first system included only low-level back-end processing of the image before displaying it on the Head-Up Display (HUD) in real-time. However, the image quality was not at the level pilots would require for confident aided landing. Therefore, to improve visual image quality the current system has been expanded to include a real-time image processor built by Lear Astronics Corp. The image processor provides real-time image enhancement and image transformation capabilities not available in the first system.

Real-time images of runways were obtained at local airports from the back of a truck, during tower test at Wright Patterson Air Force Base and flight test on a G-2 jet aircraft. These tests were sponsored under the FAA and USAF Synthetic Vision System Technology Demonstration (SVSTD) proogram. The results demonstrate the potential of 94 GHz technology for an autonomous landing system.

In section 2 of this paper the overall system architecture is discussed in more detail and in section 3 the experimental results are shown.

2.0 System Architecture

2.1 The 94 GHz FM-CW Radar

The Lear Astrronics Corp. system utilises a 94 GHz homodyne FM-CW imaging radar. The original radar system has been modified extensively to improve the RF front-end. Fig. 1 shows the detailed block digram .

In the front-end a new vertical polarized , twisted cassegrain reflector is used instead of the circular polarized, prime fed reflector used originally. This reflector and the accompanying antenna, which were designed by Malibu Research Assoc., achieves a vertical cosecant squared fan-beam pattern with a 12 degree elevation beamwidth and a 0.3 degree azimuth beamwidth. A vertical polarized antenna should enhance the radar return from grass like vegetation, which surrounds most runways.

A novel resonant antenna scanning mechanism replaces the old stepping motor assembly. This mechanism uses springs in conjunction with a torque motor, which is pulsed to overcome the effects of friction, keeping the antenna scanning in its natural resonant frequency. This is a much simpler and more compact design than the previous stepping motor assembly. The resonant antenna scan rate is 5 Hz, giving a frame rate of 10 Hz. The antenna has a horizontal scan range of 15 degrees and vertical scan range of 30 degrees. This gives an electrical radar FOV of 30 degrees in azimuth.

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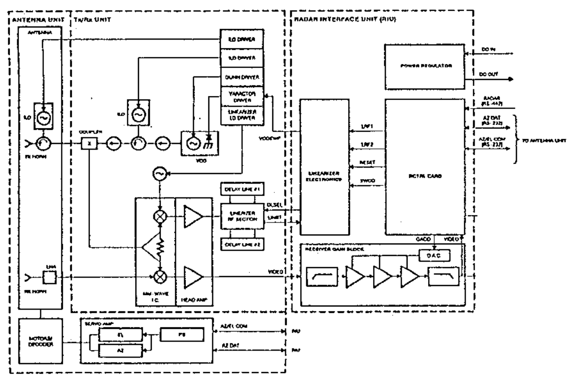

Figure 1. Detail Block Diagram of the FM-CW Radar.

An external ILO is placed at the transmitting feed horn in order to eliminate the w/g loss. To take full advantage of the future HEMT low noise amplifier, the reciever is retrofitted with an image-rejection mixer. A total improvement of 2.4 db in noise figure was measured on the bench. The 94 GHz HEMT LNA and image-rejection mixer combination provides the state of the art noise figure one can achieve at 94 GHz .

A summary of the imaging radar parameters are given in table 1.

Radar type	FM-CW/homodyne/bistatic
Center frequency	94.3 GHz
Transmitted Power	320mW
Noise Figure	8 db
Tx/Rx antenna isolation	65 db min.
Antenna Gain	41 db
Polarization	Vert.
Horizontal Beamwidth	.30 deg.
Vertical beamwidth	2.8 deg.
Scan Rate	5 Hz
Azimuth Scan Angle	+/-30 deg.
Elevation Stabilization	+/-15 deg.
Bandwidth	CW/50/100/200 MHz
Sweep Time	1.8 msec
Linearity	less than .01%
Display	C scope (elevation vs. azimuth)
Maximum process range	6000 meters, Acquisition mode
	3000 meters, Approach mode
	1500 meters, Taxi mode
Range Resolution	14 meters at 6000 meter range
	7 meters at 3000 meterrange
	3.5 meter at 1500 meter range

Table 1. Imaging Radar Parameters.

2.2 Back-End Signal and Image Processing

The goal of the back-end processing is to generate a quality image that the pilot feels comfortable in using for landing. There are three basic blocks which make up the back-end processing. First, the B-scope image is generated based on radar IF and azimuth signals, this also includes some low-level processing. Second, higher-level image enhancement is provided for visual image quality improvement, and finally C-scope transformation is done for HUD display.

The B-scope image generation is done by sampling the incoming radar IF signal at a rate of 1024 points/409 usec. Next an FFT is done on this data, obtaining a 512 point range profile of magnitude data. Then an azimuth value sampled from the antenna position sensor is attached to this data, giving one column of the B-scope image. A full B-scope image is 256 columns by 512 and is generated approximately every 100 msec. This stage in the processing also includes some gain compensation and scaling.

After the inital B-scope image generation some image enhancements are perfromed in the image processor. The image enhancements are done on the B-scope image because the C-scope image transformation results in the loss of some useful image information. The image enhancements which we have found useful in this situation are first, 2-D low pass filtering to filter out high frequency noise, second, histogram modification to improve the contrast between clutter, such as grass, and the runway, and finally edge detection to highlight the outline of the runway for the pilot. Although these algorithms are still under development we feel that these basic enhancements make a definite visual difference.

The image enhancement and transformation algorithms are very compute intensive. Thus, the image processor was designed to provide high throughput while maintaining a high degree of flexibility and expandability to accomodate any changes during development. The architecture was designed around an off-the-shelf card which uses two processors, one dedicated to high speed communication between cards and the second for high speed vector processing. This provides a scaleable architecture with maximum flexibilty in reconfiguring the system. In this way we can implement any number of image enhancement algorithms during development. The software which runs on these cards is a high-level one which adds to the ease pf development. We also use some custom hardware where computational requirements make it necessary.

Finally, the image is transformed to C-scope. This is also done using off-the-shelf general purpose processing. This transformation requires aircraft state information such as altitude, pitch, and roll. This data is obtained from aircraft instrumentation.

A block diagram of the back-end processing is shown in Fig. 2.

3.0 Expermental Results

To initially test the radar, the system was mounted in the back of a truck for access to local airport runways. Next, the system was installed in the Wright Patterson Air Force Base (WPAFB) Tower for

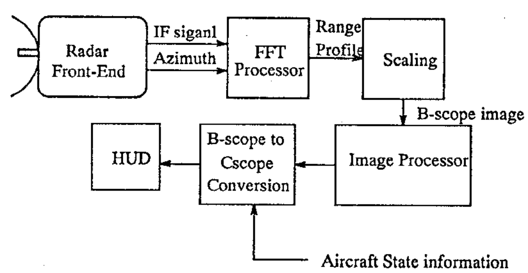

Figure 2. System processing block diagram.

tower testing and finally the system was installed in a G-2 aircraft for flight test.

Initial ground testing was done during clear and foggy weather conditions. These tests were done without a radome and at a very shallow angle, due to the limited height of the flat-bed truck. However the runway images show good contrast and excellent runway details. For example, runway lights are clearly recorgnized up to 2 km away. In Fig. 3(a) a visual picture of the runway is shown. The unenhanced B-scope radar image of this scene is shown in Fig. 3(b) while the enhanced radar image is shown in Fig. 3(c). Clearly the image enhancements improve the contrast and accentuate the runway lights in this case. This same scene was imaged during fog without considerable degradation, as is expected for 94 GHz.

Several valuable lessons were learned during ground and flight tests. First, we found that by slowing the antenna scan rate we could significantly improve the image quality by integration. Unfortunately this comes at a cost of a reduced frame rate which could cause some discomfort to the pilot. We will investigate this further in future flight tests. Second, due to the narrow elevation beamwidth of this antenna we had to implement an active pitch stabilization scheme to keep the antenna consistantly focussed on the runway regardless of aircraft pitch angle. This improved image quality dramatically. Third, we should have tested the radar with the radome on the ground. We experienced radome losses and reflection beyond our expectations when we entered the flight test. In the future we will experiment with different radome materials and shapes to minize this effect becasue the radome is a critical element of the system.

At WPAFB the system was intalled in a 75 meter tower looking down a 3500 m in-active runway. Images of the runway were clearly visable up to 3000 m away in clear weather conditions. In figure 4(a) a camera image from the top of the tower is shown. Figure 4(b) shows the enhanced B-scope radar image and figure 4(c) shows the enhanced C-scope radar image.

After the WPAFB tower tests the system was installed on a G-2 aircraft leased from Petersen Aviation of Van Nuys CA. with TRW as the system integrator. Figure 5 shows the location of the imaging radar front-end on the G-2 nose . Unfortunately, due to the tight schedule of this program only 5 flight tests were taken adding up to approximately 10 hours of flight time. During these flights test pilots were able to identify the runaway at an altitude of approximately 150 to 200 feet (3000 to 4000 ft range). The range reduction was partialy due to external ILO failure and radome problems at 94 GHz. No images were available at the time of this publication.

4.0 Conclusions

The overall performance of the current system is significantly better than that of the second system. The 94 GHz HEMT LNA and image-rejection mixer combination definitley improved the noise figure of this system. At this moment it is not clear whether or not our switch to vertical polarization has given us significant improvement in image quality for most runway images. The addition of image enhancement capabilities to our system has given us a better understanding of 94 GHz imaging and seems to give a general improvement to most runway images. This is an area which we are still actively pursuing. We have found that the computaional complexity is the limiting factor in the amount of image enhancements which can be done.

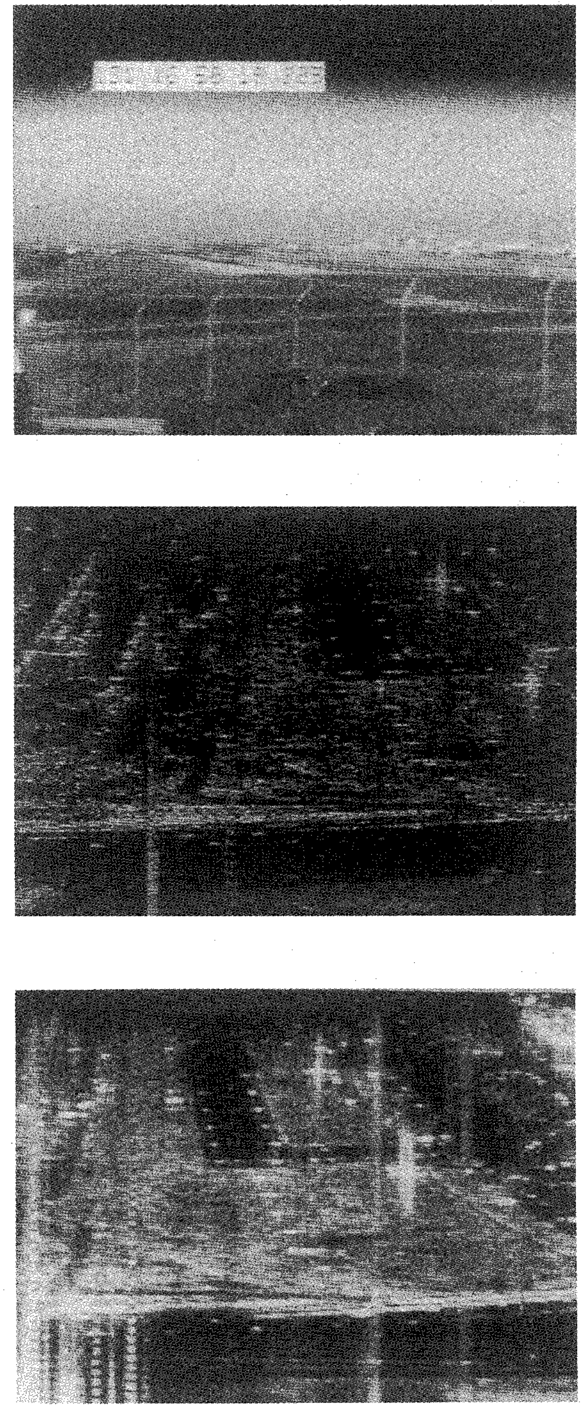

Figure 3. Image taken at LAX (a) video imgage. (b) Unprocessed B-scope image. (c) Processed B-scope image.

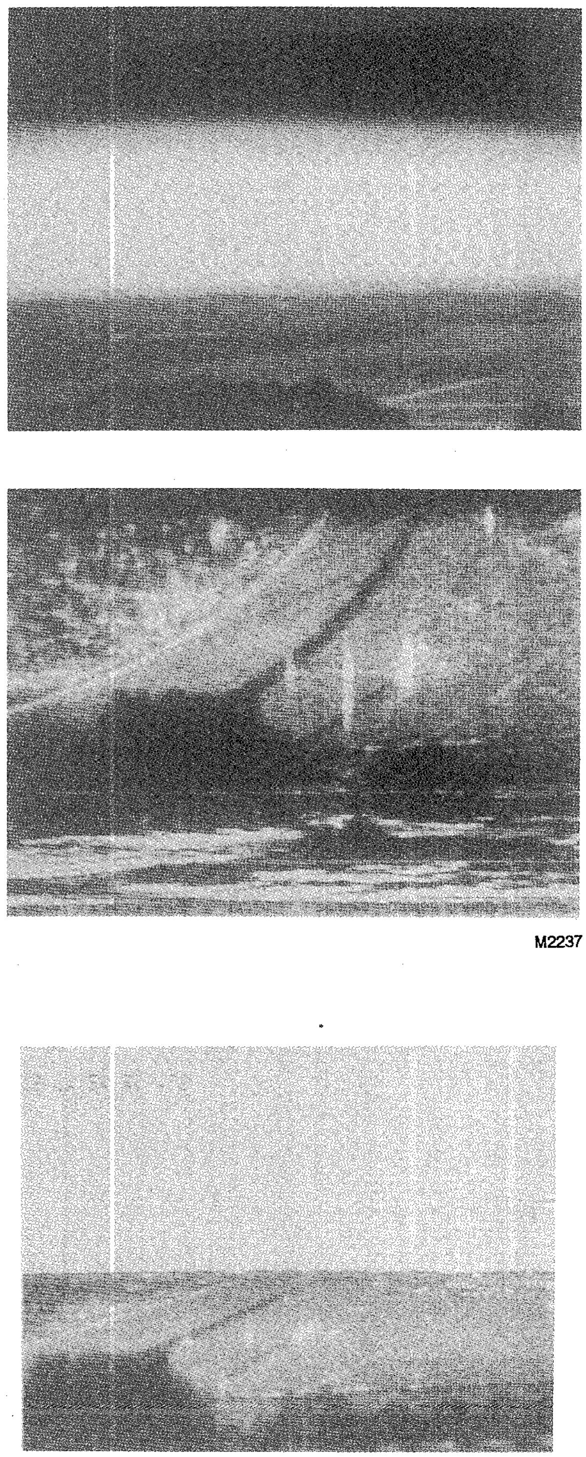

Figure 4. Image taken at WPAFB (a) video image. (b) Processed B-scope image. (c) Processed C-scope image.

In general we have shown that using a 94 GHz FM-CW imaging radar with real-time image enhancement we can produce runway images which in the future could be used for autonomous aircraft landing in adverse weather. Future flights will provide additional testing and modifications of the system towards the final goal of FAA certification.

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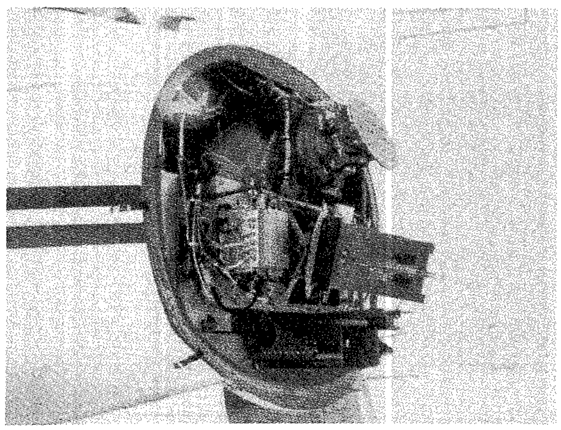

Figure 5. Nose of the G-2 aircraft with antenna installed.