



**Innovations Deserving
Exploratory Analysis Programs**

Highway IDEA Program

*Smart Array Antenna for NDE of FRP-Wrapped Concrete
Bridge Members*

Final Report for Highway IDEA Project 109

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TRANSPORTATION RESEARCH BOARD
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**Smart Array Antenna for NDE
of FRP-Wrapped Concrete Bridge Members**

IDEA Program Final Report

For the period 1/1/2005 through 9/30/2006

NCHRP 109

Prepared for the IDEA Program
Transportation Research Board
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By

Maria Q. Feng
Newport Sensors, Inc.

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TABLE OF CONTENTS

Acknowledgement

Table of Contents

Executive Summary	4
1. IDEA Product.....	5
2. Concept and Innovation	6
3. Investigation	9
4. Plans for Implementation	30
Conclusion.....	31
References	33

EXECUTIVE SUMMARY

Fiber reinforced polymer (FRP) composites have emerged as a cost-effective alternative to traditional construction materials for strengthening, retrofitting and repairing the nation's aging highway bridges (Loud and Kliger, 2001). However, the lack of reliable tools for nondestructive evaluation (NDE) of long-term conditions of FRP-rehabilitated bridges, particularly internal damage concealed by the FRP wrapping, prevents wide deployment of FRP in the field. This IDEA project develops an innovative smart antenna array concept into a high-performance NDE technology for in-situ damage detection of FRP-wrapped concrete bridge members. The array consists of multiple antenna elements actively controlled by sophisticated electronics and software. Damage targeted by the proposed technology at the present project includes debonds (air voids) between concrete and FRP wrapping, and debonds between layers of a multi-layered FRP composites. Such invisible damage (hidden under the FRP wrapping) is detected by illuminating the structure with microwaves from the antenna array and comparing the scattered microwave signals, received by the array, with a reference signal obtained at a point involving no damage on the same structure. The array can electronically scan a focused microwave beam through an area of eight square inches at a time in approximately one second. The novel wave focusing technique enables a high signal to noise ratio, a great inspection depth, and real-time damage assessment. Such high performance functions are beyond the capacities of existing NDE technologies and offer unique advantages for assessing internal damage in FRP or FRP-wrapped concrete structures.

Under the support of the IDEA funding, the project team successfully developed solutions to overcome the technical risks associated with the proposed technology, such as the difficulties in accurately focusing microwaves deep into concrete and FRP composites. Guided by an advisory board consisting of bridge owners - future users of the technology, the project team developed technical specifications, and then prototyped an antenna system consisting of a six array antenna unit, together with its sophisticated control system and software. Based on extensive evaluation tests on concrete-FRP specimens involving debonds of various sizes, the design of the system was further improved. The effectiveness of the improved smart array antenna system in detecting and quantifying the debonds between FRP wrapping and concrete was experimentally demonstrated.

Based on the success of this IDEA project, Newport Sensors, Inc. is well positioned to move to product transfer and implementation stage. Successful commercialization of the smart array antenna-based NDE technology will promote wide deployment of FRP for cost-effective renewal of highway bridges and enhance the safety of the nation's transportation infrastructure.

1. IDEA PRODCUT

This IDEA project developed an innovative smart antenna array concept into a high-performance nondestructive evaluation (NDE) technology for in-situ condition assessment of fiber reinforced polymer (FRP)-wrapped (or jacketed) structural members of concrete bridges. The array consists of multiple miniature antenna elements actively controlled by sophisticated electronics and software to focus microwave (in a GHz range) to a point of inspection. Invisible damage, such as air voids, cracks, debonds between FRP jackets and concrete, is detected by scanning the focused microwave beam and analyzing the scattered wave signals.

The proposed smart antenna array represents significant technological advancement and advantages over the currently available NDE technologies. First, the system uses focused microwave (vs. unfocused one commonly used in ground penetrating radars), and as a result substantially increases the signal-to-noise ratio as well as the inspection depth. Second, the wave focusing and beam scanning are performed electronically by software, making it possible to investigate a large area in real time (without mechanically moving the array). Such high performance plus the light weight and portability make the proposed antenna system uniquely suitable for in-situ quantitative evaluation of damage in FRP-wrapped concrete members.

In addition to a new knowledgebase regarding the innovative use of microwaves for NDE of concrete-FRP structures, this project delivered a prototype smart array antenna system consisting of a hand-held antenna unit and a control unit (with built-in power supply), together with a software package for operation control, signal processing, and display in real time.

2. CONCEPT AND INNOVATION

A smart antenna array, as illustrated in Figure 1, was proposed in this IDEA project. Different from the *passive* lenses (with a fixed focusing distance) developed earlier by the project team (Feng, et al, 2002), the proposed smart antenna array consists of a number of (12 in this example) smart antenna elements and microwave sent from each of the elements is *actively* focused to a common point of inspection on the FRP-concrete interface, for example, and the focusing point can be quickly changed, all under the control of sophisticated electronics and software. Each antenna is a planar microstrip slot or patch antenna, making the system lightweight and portable, and thus suitable for in-situ detection of invisible debonds (air voids) between FRP jackets and concrete structural members caused by poor installation workmanship, as well as concrete damage concealed by the FRP jackets caused by earthquakes and other destructive loading.

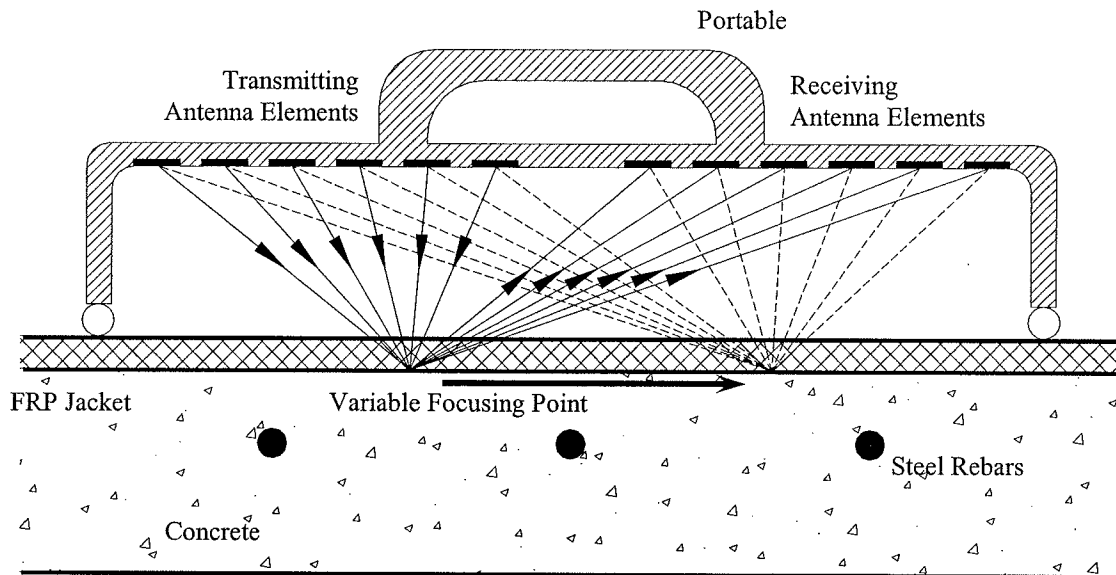


FIGURE 1 Smart antenna array for NDE of FRP-wrapped concrete structure.

The proposed smart antenna array technology was made possible by synergetic integration of the following technical innovations.

Innovation #1 – Use of focused microwaves

Conventional microwave-based NDE technology is based on illumination of an object with plane (unfocused) waves (Kak and Slaney, 1988, Rhim and Büyüköztürk, O., 2000).

However, earlier studies performed by this project team have shown that focused microwave can achieve a much higher signal-to-noise ratio than the unfocused one and thus are much more capable of detecting small defects (Feng, et al, 2002, Kim, et al, 2003, Kim, et al, 2004). As illustrated in Figure 1, where microwaves are focused on the bonding interface of an FRP-jacketed reinforced concrete column, by focusing the wave energy to the region of interest (in this case the bonding interface), the scattering (reflections) from the elements in the other regions, such as steel rebars, will be reduced, and thus the signal-to-noise ratio can be improved and as a result small voids and debonds can be detected.

Innovation #2 – Smart beam scanning

With the smart antenna array, a large area can be efficiently inspected by quickly changing the focusing point (i.e., the direction and distance of the main microwave beam) of the antenna array by sophisticated electronics and software. To be more specific, the main beam direction is controlled by adjusting the phase of the exciting current of each antenna element in the array. This operation is referred to as beam scanning. Figure 2 shows an example of beam scanning by a two antenna arrays: One for transmitting illuminating microwave and the other for receiving reflected wave.

The more the number of antenna elements in the array, the sharper the focused microwave beam becomes (that means higher resolution and deeper inspection). Figure 3(a) shows the radiation pattern of an 8-element antenna array, obtained from the simulation analysis by the project team. The amplitude and phase of the current fed into each element are same. The main beam of the antenna array points at the broadside direction. If a phase difference is introduced between the elements, e.g. 45° , the mean beam of the antenna array will be steered to about 12° off from the broadside direction as shown in Figure 3(b).

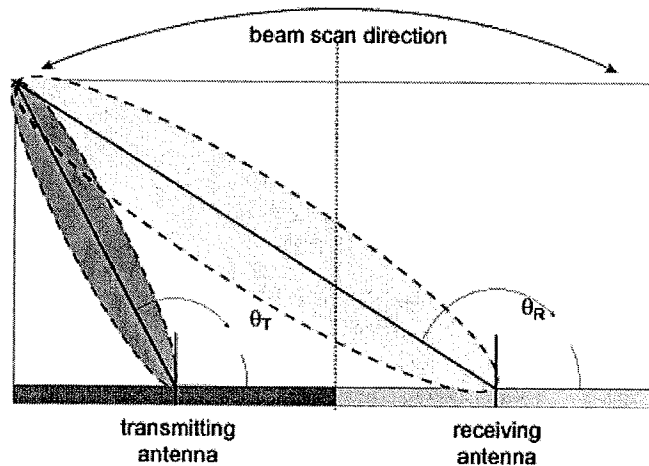
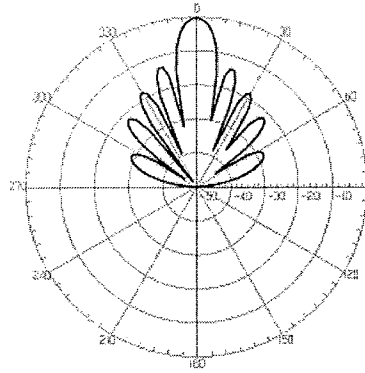
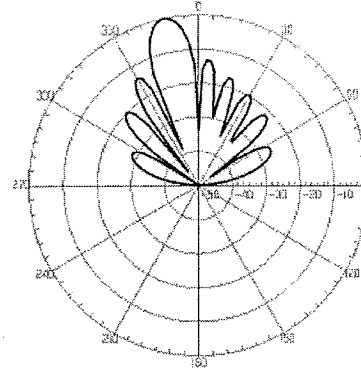


FIGURE 2 Beam scanning using a smart antenna array



(a) 8-Element Array w/ Equal Amplitude and Equal Phase



(b) 8-Element Array w/ Equal Amplitude and 45° Phase Difference

FIGURE 3 Smart antenna array

3. INVESTIGATION

3.1 PROJECT TASKS

This IDEA project consists of two phases of study. The research tasks and milestones proposed for Phase I Prototype Development and Phase II Performance Evaluation and Improvement are as follows:

Phase I. Prototype Development

Tasks: (1) To determine specifications of the prototype through a series of simulation analysis and laboratory testing of a variety of antenna arrays
(2) To design and fabricate antenna systems with control module and software.

Deliverable: Prototype smart antenna array system including hardware and software

TABLE 1 Research Plan and Milestones

Tasks	PHASE I												PHASE II								
	Q1			Q2			Q3			Q4			Q1			Q2			Q3		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
<u>Task 1. Design and Simulation</u>																					
<u>Task 1.1 Technical Specifications</u>																					
<u>Task 1.2 Design of Smart Antenna Array</u>																					
<u>Task 1.3 Evaluation through Simulation</u>																					
<u>Task 2. Fabrication and Integration of Antenna Array</u>																					
<u>Task 2.1 Fabrication & testing of Antennas</u>																					
<u>Task 2.2 Integration of Software-Hardware</u>																					
<u>Task 3. Performance Evaluation Tests</u>																					
<u>Task 3.1 Specimen</u>																					
<u>Task 3.2 Evaluation Tests</u>																					

Milestones: (1) Technical specifications and design of the prototype by the end of quarter 2, Year 1
(2) Fabrication of antenna array and control module by the end of quarter 3, Year 1

(3) Development of software and integration with hardware by the end of Year 1

Phase II. Performance Evaluation and Improvement

- Tasks: (1) To evaluate the prototype system through experiments on the laboratory specimen and in the field. Performance in terms of signal to noise ratio, inspection resolution, and operational ease will be evaluated
(2) To improve the design of the antenna system based on the evaluation results
- Deliverable: Improved prototype smart antenna array system
- Milestones: (1) Laboratory and field tests by the end of quarter 2, Year 2
(2) Improved design by the end of quarter 3, Year 2

3.2 INVESTIGATION APPROACHES AND RESULTS

3.2.1 Phase I

Task 1. Design of Smart Array Antenna and Simulation Analysis

Task 1.1 Determination of technical specification

Damage targeted by the proposed NDE technology at the present project includes (1) debonds (air voids) between concrete structural member (a column or a superstructure member) and its FRP wrapping, and (2) debonds between layers of a multi-layer FRP wrapping. In order to determine the technical specifications of the proposed smart array antenna system, we performed extensive literature surveys (to study the currently available state DOTs' inspection requirements) and formed an advisory board consisting of several potential users in state DOT (including Caltrans and NY State DOT), FRP suppliers, contractors, structural inspectors, and FRP experts in the Aerospace Corporation. The project team also had opportunities to interact with many members of the NCHRP-IDEA Committee. Based on the literature survey and the advice from these future users, the requirements for the smart antenna system and accordingly the technical specifications of the prototype have been determined as follows:

- **Frequency:** 10GHz (CW mode)
- **Investigation depth:** 2.5 cm (1 in)
- **Minimum detectable debond thickness:** 1.3 mm (.05 in)
- **Scan interval:** 1 cm (0.39 in) ~ 3 cm (1.18 in) adjustable
- **Scan area covered by one measurement:** 2.5 × 25 cm (0.98 × 7.87 in)
- **Scan time for one scan area:** 1 second
- **Weight of the portable prototype:** < 1kg (2.2 lbs)
- **Dimension of prototype:** 10 × 30 × 20 cm (4 × 12 × 8 in)
- **Power supply:** 15V DC, built-in rechargeable battery
- **Battery life:** 4 hours per charge
- **Operating temperature:** -10°C to 40°C ambient

It is noted that a significant advantage of the electronic scanning using a phase array antenna is its high scanning speed (1 second for an area of approximately 8 square inches). Such a speed make is feasible to apply the technology in real-life bridge structures.

In order to determine the configuration of the array antenna including the number of array antenna, we performed a series of numerical simulations and experiments. As a result, we decided the configuration shown in Figure 4 for the smart array antenna.

Each array antenna is connected with phase shifters and switches, which activate one transmitting and receiving antenna at a time. By switching on and off these phased array

antennas with adjusting the scan angle by phase shifter, the measurement line, which is 24cm long, can be quickly scanned without moving the antenna. The scan angles of each phased array antenna are 14.02° and 26.6° . These angles can be obtained 3cm measurement interval.

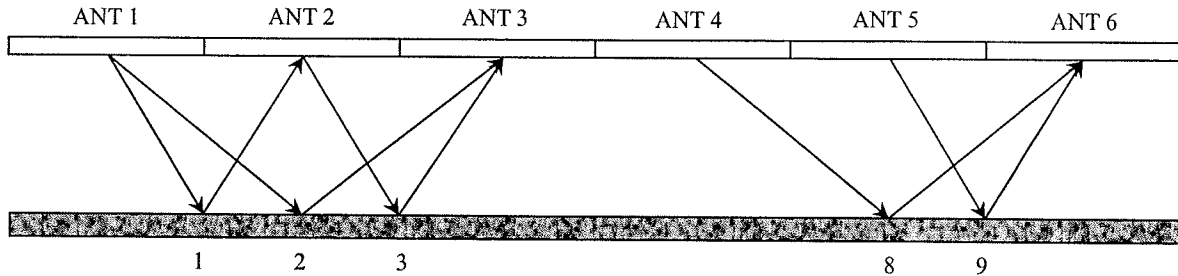


FIGURE 4 Scanning mechanism of smart array antenna system

Tasks 1.2 and 1.3 Design of smart antenna array & simulation analysis

The design of smart array antenna system started with a system block diagram as shown in Figure 5. The prototype system consists of three modules including (1) a controller and a power supplier, (2) the transceiver (transmitter and receiver), and (3) array antennas including feed network. For the operational ease, power supply is divided into two parts; one supports the controller power while the other supports the transmitter/receiver and feed network. In the transceiver (transmitter and receiver) module, the operation status can be reported into the controller in real time by using the threshold detectors. By doing so, the operator can notices and investigates any problems during the operation immediately.

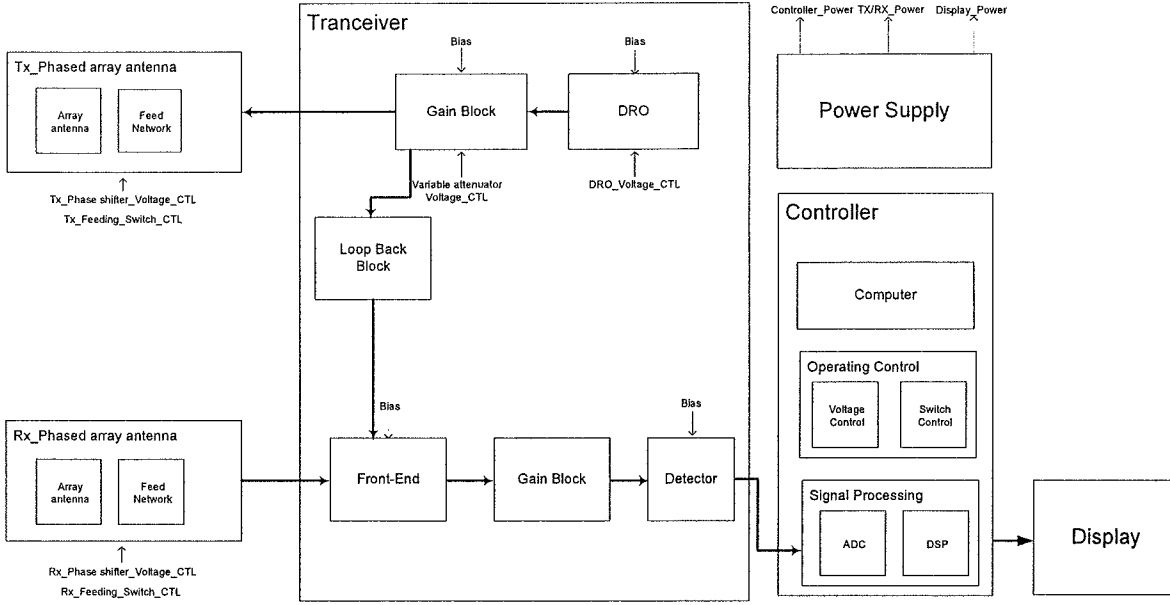


FIGURE 5 System block diagram of prototype smart array antenna system.

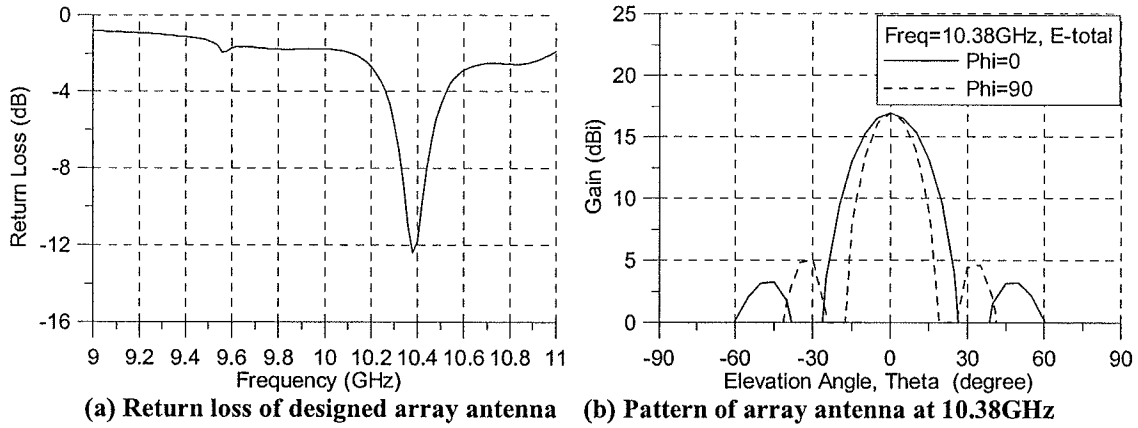


FIGURE 6 Design of array antenna.

Array Antenna: As described in the previous technical specifications, six array antennas were integrated for transmitting and receiving signals. Each array antenna consists of 3×4 antenna elements in a matrix form. The performance testing results of the array antenna are shown in Figure 6, indicating 16dBi gain and 3.4cm beamwidth (12cm height) at 1dB level of peak value. In other words, the low cost, compact array antenna developed in this project produced desired high performance.

Feeding Network: The feed network consists of several switches and phase shifters. We designed and fabricated an analog type phase shifter for the verification of the proposed concept. The array antenna was connected with a 360° phase shifter and the beam direction of the antenna was measured at various phase angles. As a result, we verified that the designed phase shifter is capable of shifting the beam. Since the prototype needs bi-directional phase shifting (to the left and to the right), we have decided to use a digital type phase shifter for the prototype. This prototype is easier to operate using digital control. In addition to the design of the phase shifter, we have developed feeding network that requires several RF switches including SP2T and SP5T. We also designed the logic of selecting the transmitting and receiving antennas, as shown in Figure 7. We also ordered the components during the quarter.

Transceiver: In order to minimize the size of module and reduce the housing cost, we decided to combine the transmitter and receiver into one unit of transceiver. The transceiver unit consists of a DRO (signal source), a band pass filter, power amplifiers, an attenuator, and several detectors, which also can be used to check the operating status. We also designed housing for the transceiver to minimize the interference of the transceiver with the surrounding environments. The design of the transceiver is shown in Figure 8.

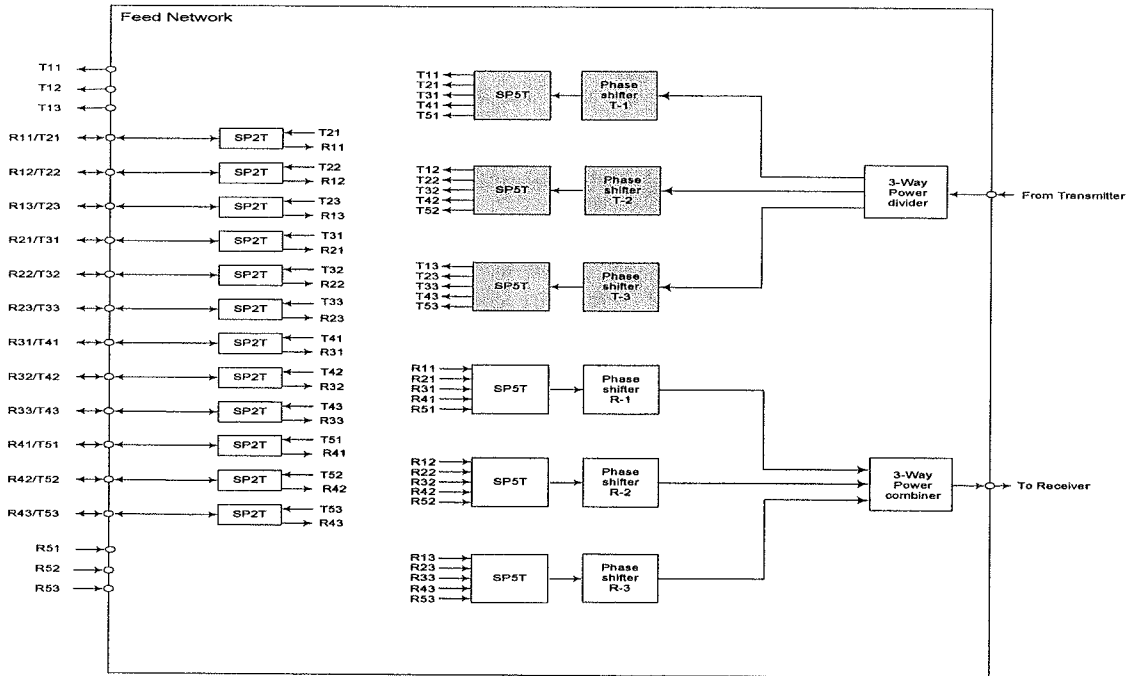


FIGURE 7 Design of feeding network

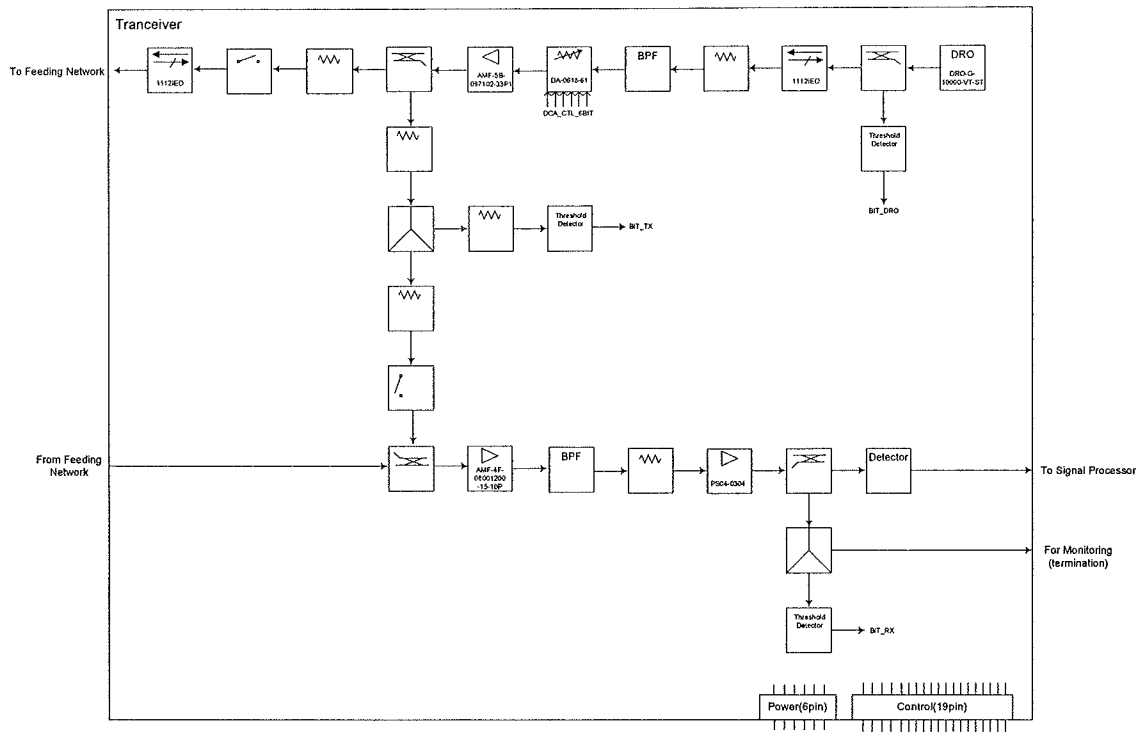


FIGURE 8 Design of transceiver

Task 2. Fabrication & Integration of Smart Array Antenna

Task 2.1 Fabrication of array antenna, feeding network, and transceiver of the system

Based on the design, component testing results, and simulation, we fabricated a prototype smart array antenna system. The system primarily consists of an array antenna with feed network, a transceiver, a controller, and power supply. We also fabricated the housing of transceiver, feed network, and power supply,

Considering the required small size of element, complicated feed network, and isolation between the feed network and antenna, an aperture coupled microstrip antenna was used as an antenna element of the antenna array.

The design of the each array antenna is shown in Figure 9. Based on the design, we fabricated array antennas as shown in Figure 10. The smart antenna system contains six integrated array antennas and each of them has 3 arrays of 4 elements (3×4 array). Each antenna is fed by three different phases in order to control the main beam direction. During the measurement, only two of the array antennas are activated as a transmitter and a receiver, and the others are deactivated. The operation is controlled by the feed network consisting of the phase shifters and the switches.

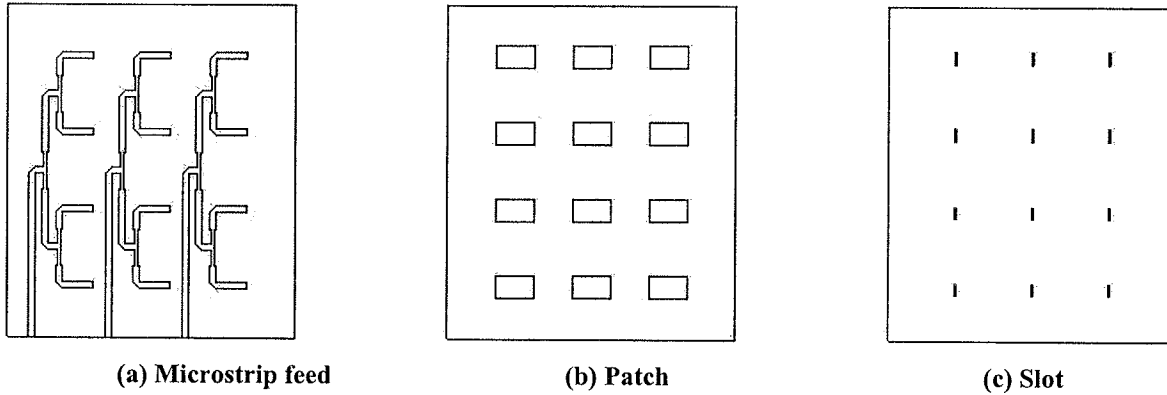
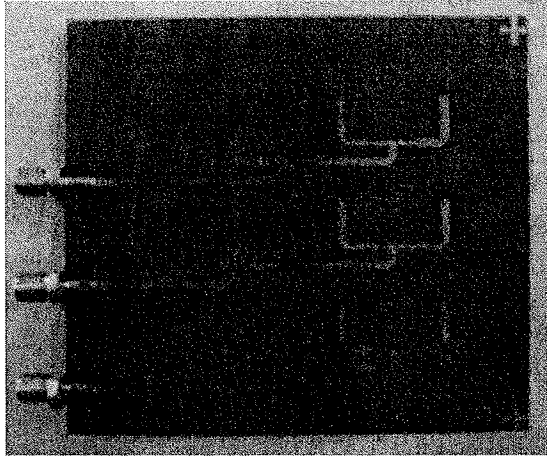
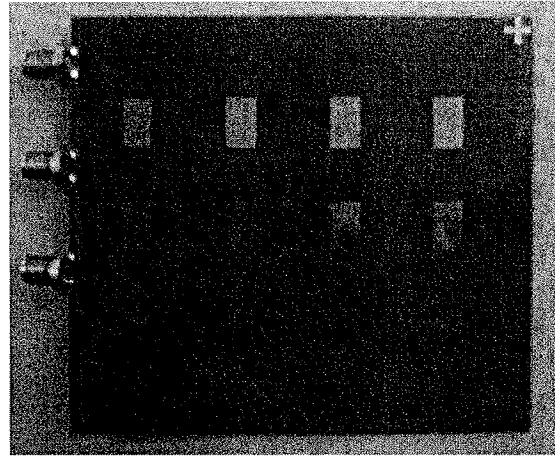


FIGURE 9 Design of each array antenna



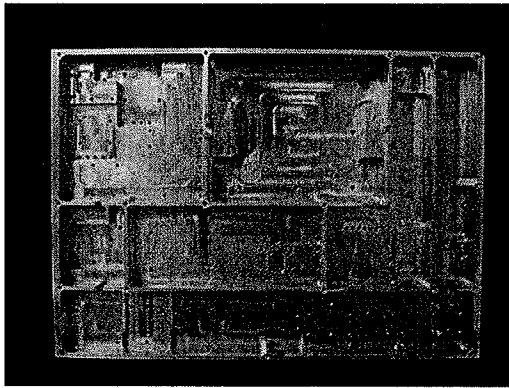
(a) Microstrip feed



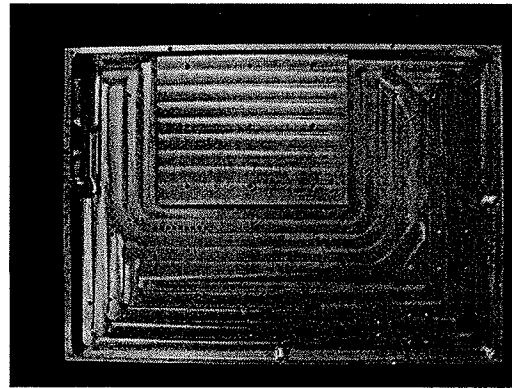
(b) Patch

FIGURE 10 Fabricated array antenna

We then fabricated the housing for the transceiver, which houses several components and also serves as a ground for them. The housing is made by using aluminum material for its light weight and easy fabrication. First, we determined the layout of every components of transceiver, and drew a 3D CAD/CAM drawing for CNC milling process. Figure 11 shows the fabricated housing.



(a) Top view



(b) Bottom view

FIGURE 11 Fabricated housing for transceiver

We fabricated the transceiver with such RF parts as DRO, filters, power amplifiers, LNA, DCA, attenuators, and a detector. The performance of each component was experimentally tested and verified before integrating these components. In order to minimize noises and resonances, we performed extensive testing and tuning of the transceiver and modifying the housing. After numerous testing and modifications, we finalized the transceiver as shown in Figure 12, and it achieved a desired performance as shown in Figure 13.

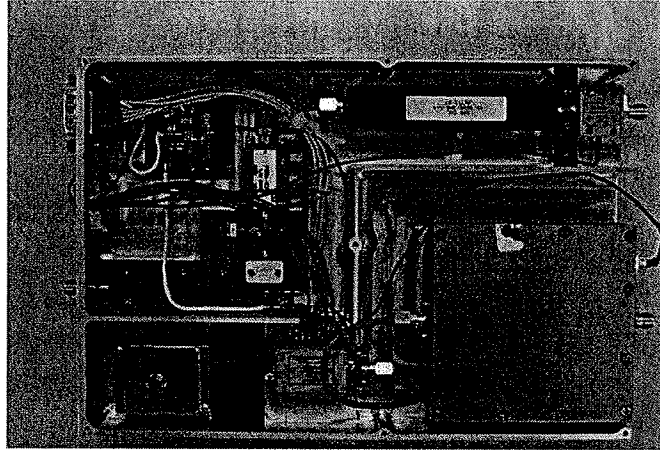


FIGURE 12 Transceiver

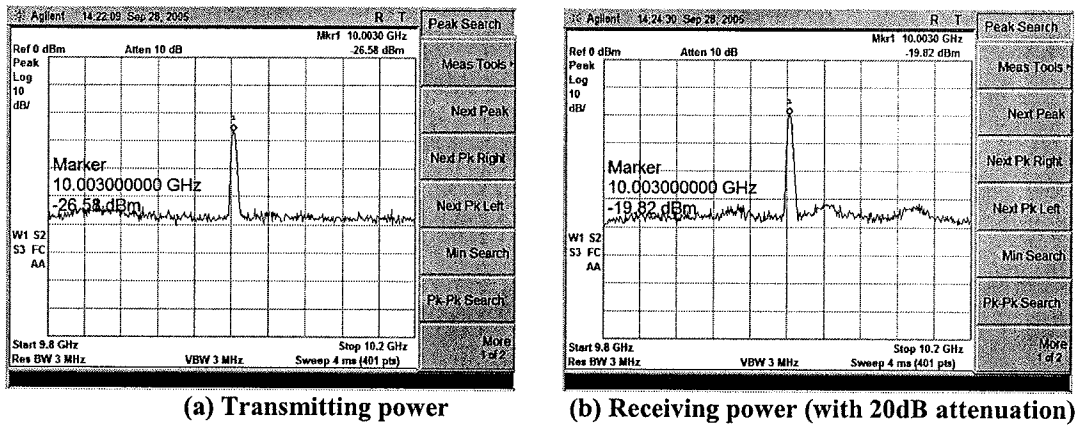
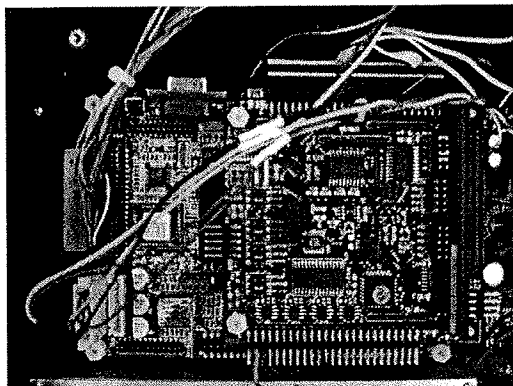


FIGURE 13 Transceiver performance

Task 2.2 Integration of software and hardware

Controller and DAQ: As described in the system design, an embedded single board computer (SBC) with PC/104 data acquisition (DAQ) board was used for controller. We acquired Model AR-B1551 manufactured by Acrosser for the SBC, and PC/104 digital and analog in/output board manufactured by ACCES I/O Product Inc. for the DAQ boards. Windows XP Embedded was installed on a compact flash memory card to play a roll of hard-drive in a regular PC. For the connection of a number of digital and analog input/output control signals, we used DB 44 and DB 62 connectors. Figure 14 shows a picture of the assembled controller.



(a) SBC & DAQ board



(b) LCD panel with touch screen

FIGURE 14 Controller with DAQ boards and LCD panel with touch screen.

Feed network: As described in the design, the feed network consists of phase shifters and several RF switches. We assembled the feed network components into a wooden case with several layers. Each component is connected by using the flexible RF cables with SMA connection, which provide shielding between the components. Figure 15 shows the fabricated feed network before connecting the RF cables.

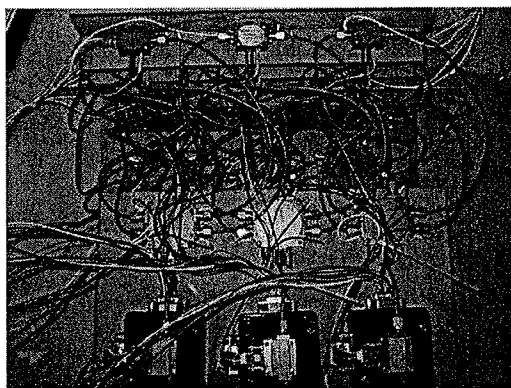


FIGURE 15 Fabricated feed network

Verification of feed networks: Before the integration of the software and hardware, we developed a testing software package and used the software to verify the control signals for the feed network. The testing software was coded based on Labview®, as shown in Figure 16.

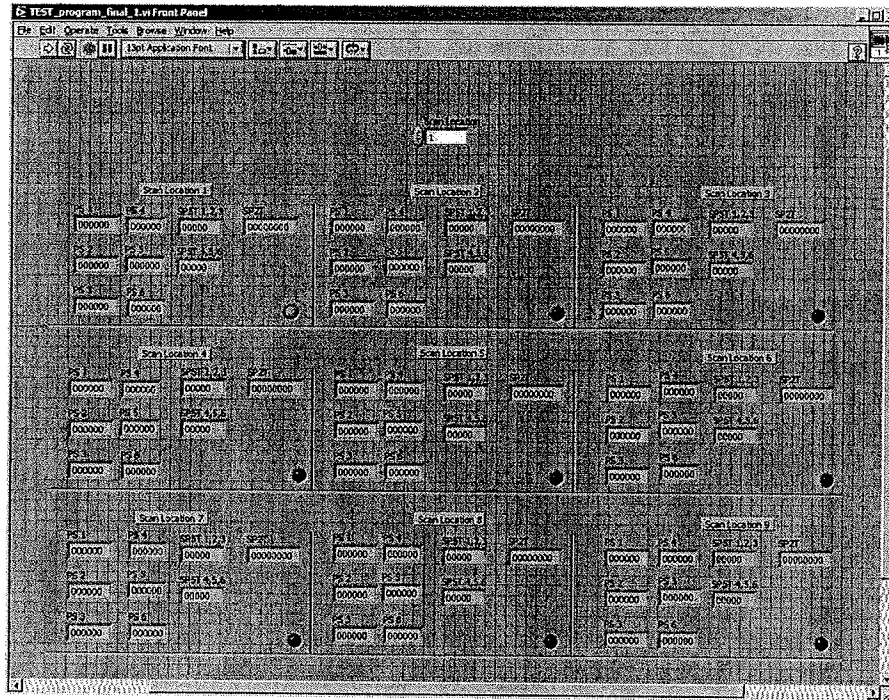
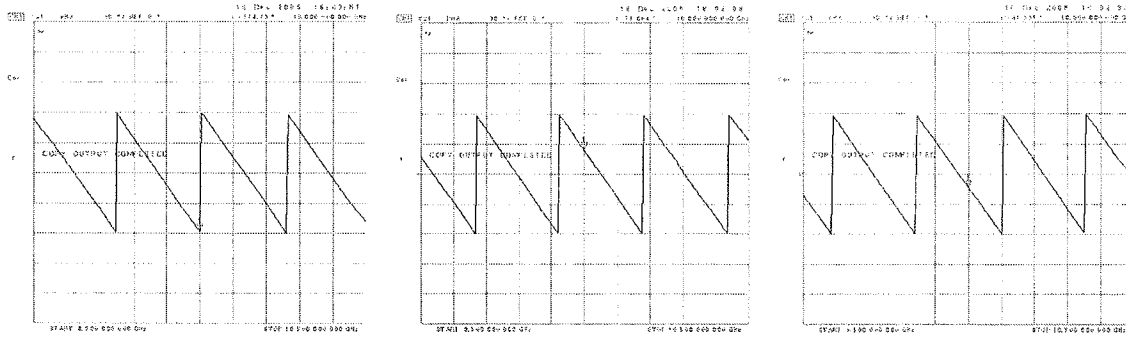


FIGURE 16 Screen shot of feed network testing software.

Using the testing software, we verify the amplitude and phase of the signals fed into each array antenna at each scan location. As an example, the phase information at feed 1, 2, and 3 is shown in Figure 17. At a certain scan location, two array antennas were activated by controlling the SP5T and SPDT RF switches. Then, three feed lines at each array antenna have the pre-calculated phase values for different scan angle, by controlling the phase shifters. There are two beam scanning angles, as explained in Task 1. In order to achieve these angles, each feed line has a phase difference of 62° and 112.5° respectively. Table 2 summarized the test results demonstrating that the feed network is working as designed.

We also experimentally confirmed that the scan time required for one scan that covers approximately 8 square inches is less than 1 second.



**FIGURE 17 Example of phase information at feed 1,2, and 3
(Antenna 1 at scan location 1)**

TABLE 2 Feed network verification test results.

Scan Location	No. of Array Antenna	No. Feed	Amplitude (dB)	Phase (°)	Phase Difference
1	1	1	-19.831	-180	
		2	-19.929	116	64
		3	-19.673	54	62
	2	1	-21.720	92	
		2	-21.254	157	-65
		3	-20.990	-144	-59
2	1	1	-20.158	-178	
		2	-19.796	67	115
		3	-19.694	-45	112
	3	1	-21.159	-22	
		2	-21.418	82	-104
		3	-21.208	-161	-117
3	2	1	-21.780	-179	
		2	-21.773	119	62
		3	-21.265	54	65
	3	1	-21.281	71	
		2	-21.303	133	-62
		3	-21.028	-160	-67
4	2	1	-21.955	-177	
		2	-21.603	71	112
		3	-21.411	-45	116
	4	1	-21.318	-11	
		2	-21.731	102	-113
		3	-21.171	-146	-112

Operation Software: We developed a software package for controlling the operation of the smart array antenna system and process the received microwaves. Major steps include (1) generating microwaves, (2) transmitting microwaves to the antennas, (3) shifting phases, (4) acquiring reflected microwaves that was received by the antennas, (5) processing the received signals to obtain the structural sub-surface image, and (6) displaying the sub-

surface image in the LCD panel. The operational flow chart shown in Figure 16 was developed, based on which the software was coded in Visual C++. A screen shot taken when the program was executed is shown in Figure 18. The program can flexibly control the parameters for the transceiver operation and the parameters for beam scanning, by using the touch panel screen. The status of the system can also be checked from the touch panel screen, as demonstrated in Figure 19.

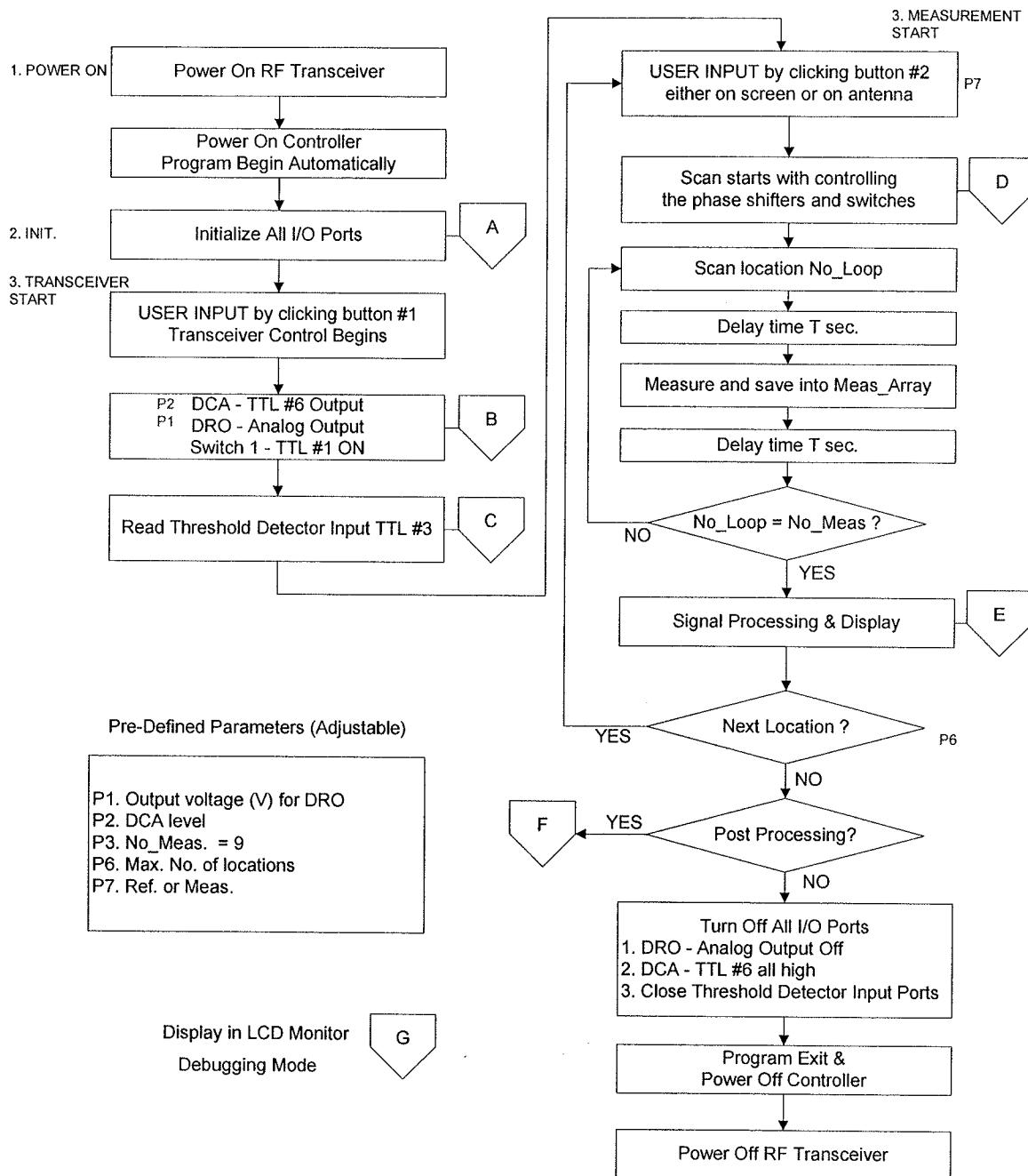


FIGURE 18 Operation flow chart for the software

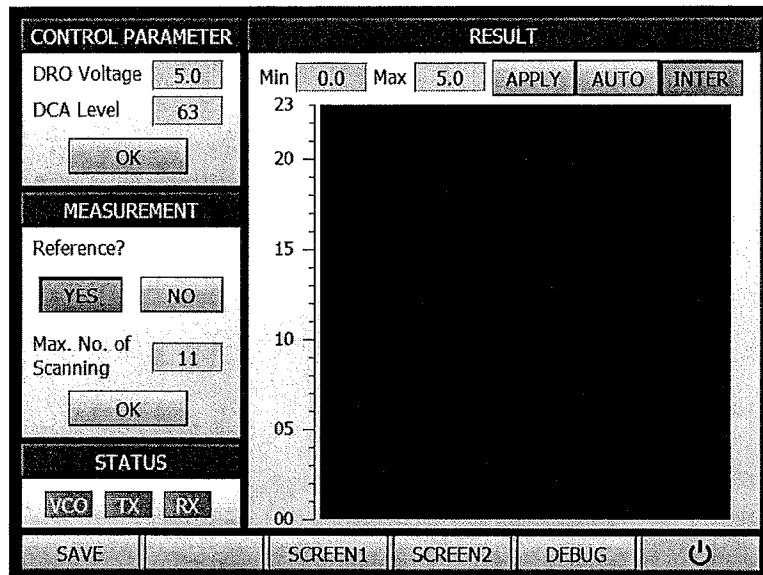


FIGURE 19 Screen shot of the control/processing software.

Power Supply: We modified the design of the power supply, which keeping the original specifications, in order to further reduce its size. We fabricated one printed circuit board (PCB) to integrate all the parts. The improved power supply board requires two rechargeable Li-Poly batteries and has two switches: one is for the controller and the other for the transceiver and feed network. Figure 20 shows the picture of improved power supply with the battery.

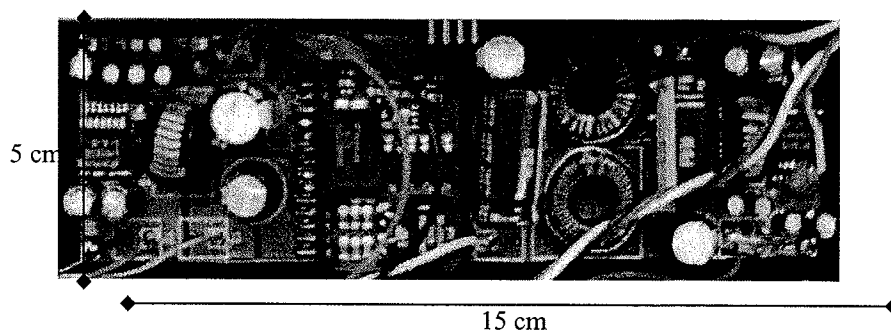


FIGURE 20 Power supply

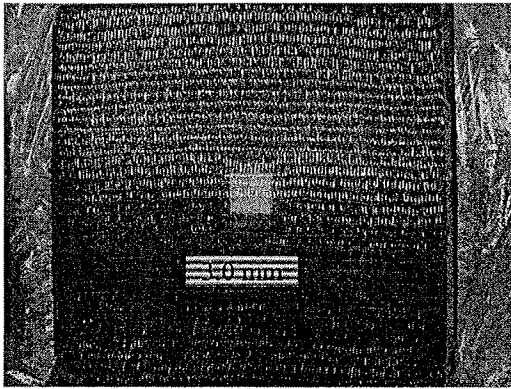
3.2.2 Phase II

Task 3. Performance evaluation tests

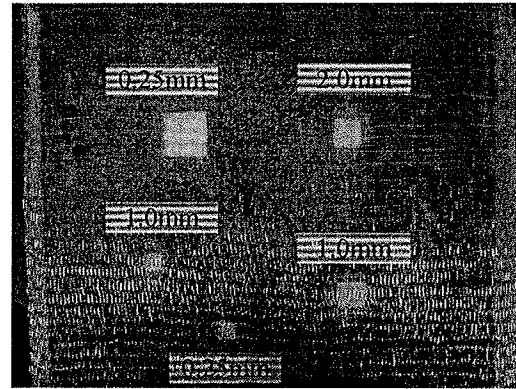
Task 3.1 Design the scenarios and construction of specimen

The performance of the prototype smart array antenna system was evaluated using concrete block specimens wrapped with glass and carbon FRP sheets. Different damage scenarios were created including various sizes and depths of debonding areas between concrete and FRP, and between layers of a multi-layered FRP composite sheet. The glass FRP composite materials were supplied by Fyfe Co., in San Diego, CA. Debonding areas of different depths were artificially created by inserting Styrofoam that has the similar dielectric property to air, and air injection during the curing of FRP.

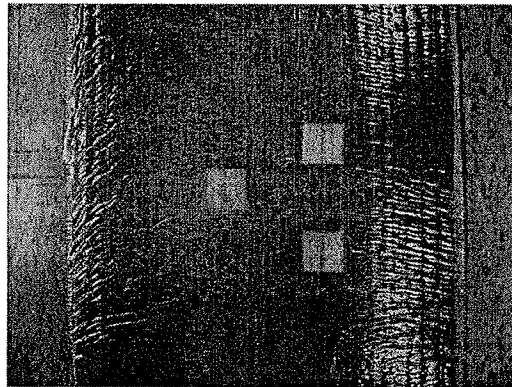
Figure 21 shows some of the testing specimens. Specimens #1 and 2 are concrete blocks covered with 2 layers of hand-laid glass FRP wrapping with debonds of various gap thicknesses. Specimen #3 is an hand-laid FRP sheet containing 7 layers FRP composites, which have debonding (Styrofoam) between the layers. Specimen #4 is a pre-fabricated (protrude) bridge deck model.



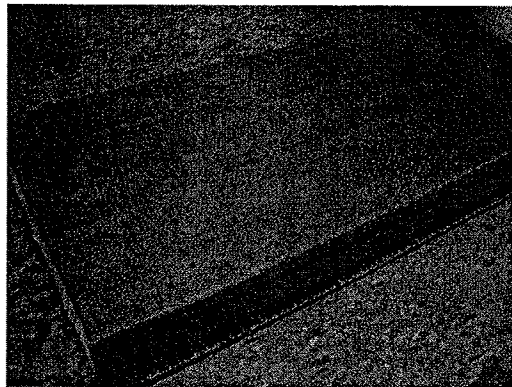
(a) Specimen #1 (1 Debonding Area)



(b) Specimen #2 (5 Debonding Areas)



(c) Specimen # 3 (Debonding between Layers of a 7-layer composites)



(d) Specimen #4 (FRP deck w/ honeycomb structure)

FIGURE 21 Specimens for performance evaluation test

Task 3.2 Evaluation tests of the prototype

We evaluated the prototype by first testing one of the concrete block samples (Specimen #1) involving a large debonding area, as shown in Figure 22. The specimen has an artificially included debonding of 5cm X 5cm X 3mm (depth). The phased array antennas were assembled on a wooden frame and connected with the feed network using the cables having same length to avoid a signal loss difference. Figure 23 shows the test setup.

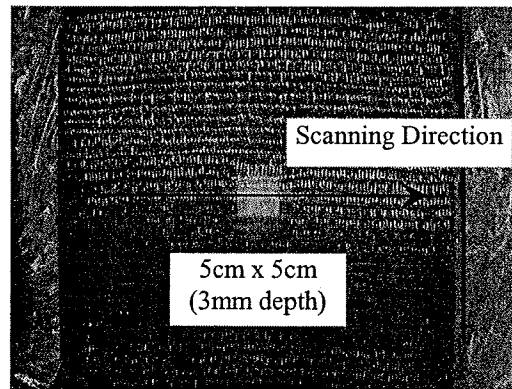


FIGURE 22 Concrete specimen used for the first evaluation test.

The results from the first evaluation test were not good: the coupling inside the feed network was so high that the signal differences at the antenna ends were not detected. We redeveloped the feed network in order to avoid the coupling, but the signal to noise ratio was still low.

After extensive testing, we finally found out the main problem was due to the interference with the power divider. We redesigned power divider with strong shielding and solved the interference problem. Figure 24 shows a test results after modifying the system. Apparently, the result indicates the location of the debonding, which is located at scanning location of 5. When we set a threshold as 2.5dB, the exact location can be detected.

The threshold is for the comparison between the received scattered signal and a reference signal that is measured at a location involving no damage at the same structure. Obviously, the threshold value needs to be carefully studied, because a smaller threshold may result in the interpretation of noise as “damage”. This value should be studied based on extensive field evaluation tests (which is beyond the scope of this project), so that we can determine whether this threshold is common to all applications or will it vary by structural type and configuration?

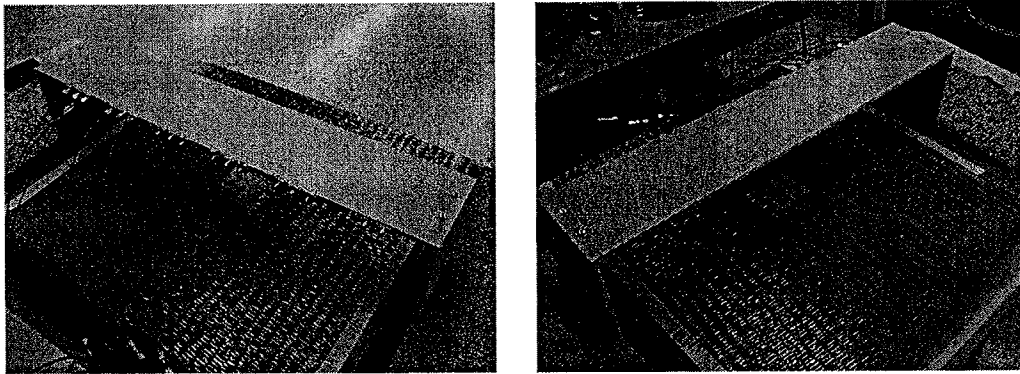


FIGURE 23 Preliminary test setup.

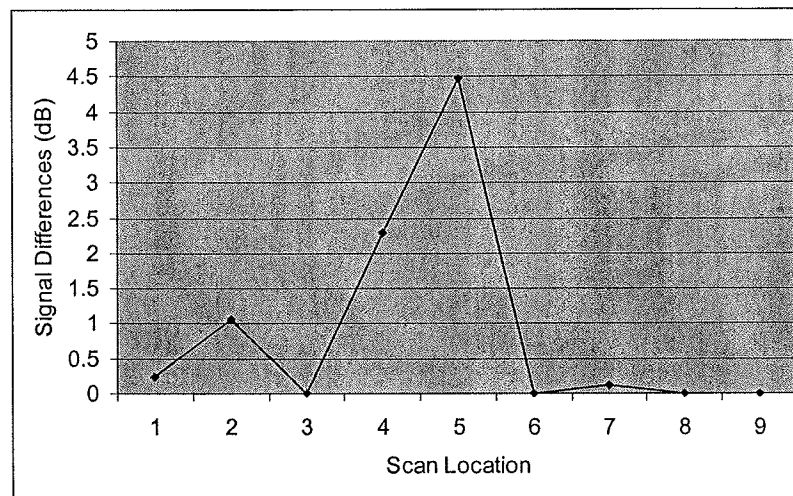


FIGURE 24 Preliminary test results

We further processed the results into a sub-surface image that enables us clearly visualize the location and size of the debonding areas. All the defects built in the specimens shown in Figure. 21 were successfully detected from the scanned imaging. As an example, Figures 25 and 26 show the scanned real-time images respectively on an FRP-wrapped concrete block (Specimen #2) and a seven-layer FRP composites (Specimen #3). The concrete block is wrapped with two layers of E-glass FRP sheets bonded by adhesive epoxy, and the bonding layer involves two debonds with dimensions of 4cmX4cmX1.5mm and 4cmX4cmX1.0mm. On the other hand, the seven-layer E-glass FRP composites contain similar debonds between the layers. In both specimens, the debonds were successfully detected and displayed as images in real time.

A future study, however, is needed to distinguish the debonding area in the bonding interface between a layered FRP wrapping and concrete from a debonding area between layers of the FRP wrapping.

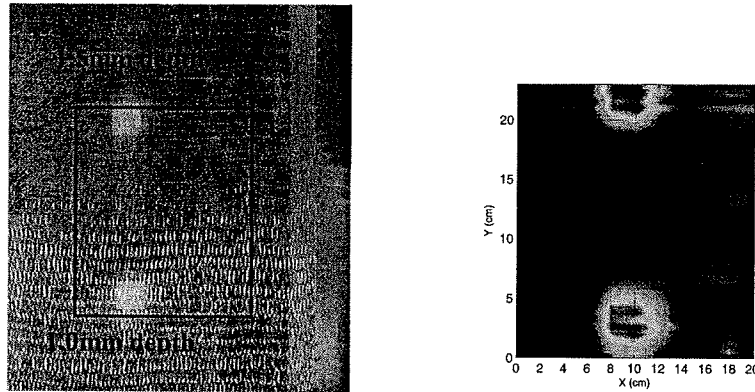


FIGURE 25 Real-Time Image of a Scanned Area on FRP-Wrapped Concrete

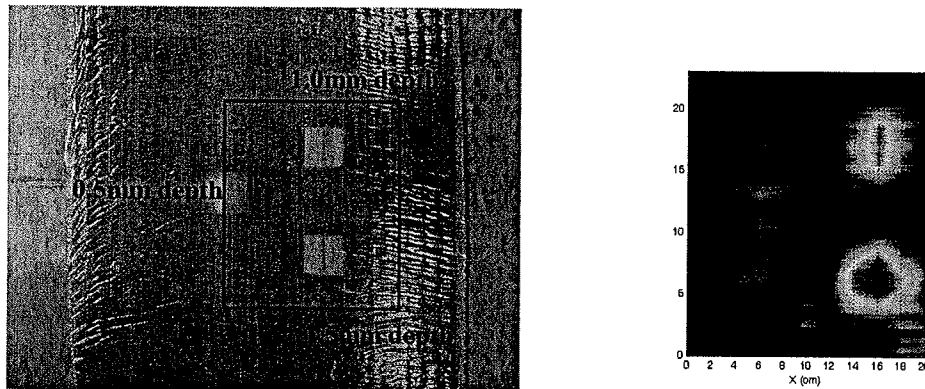
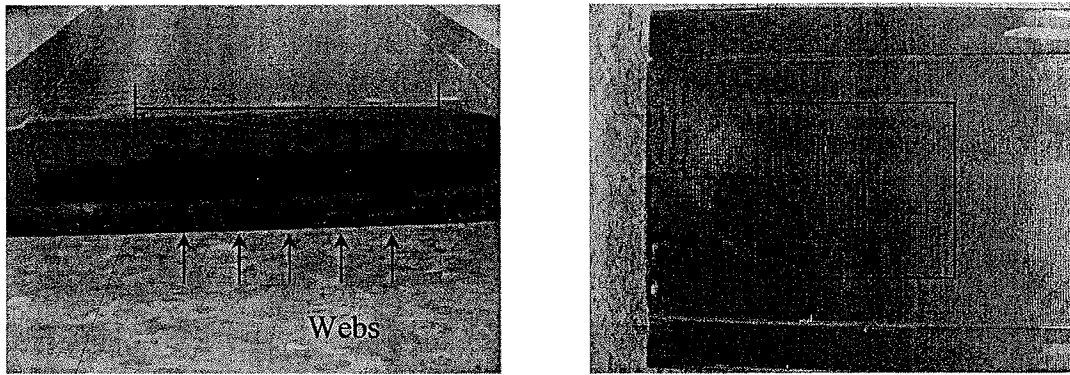
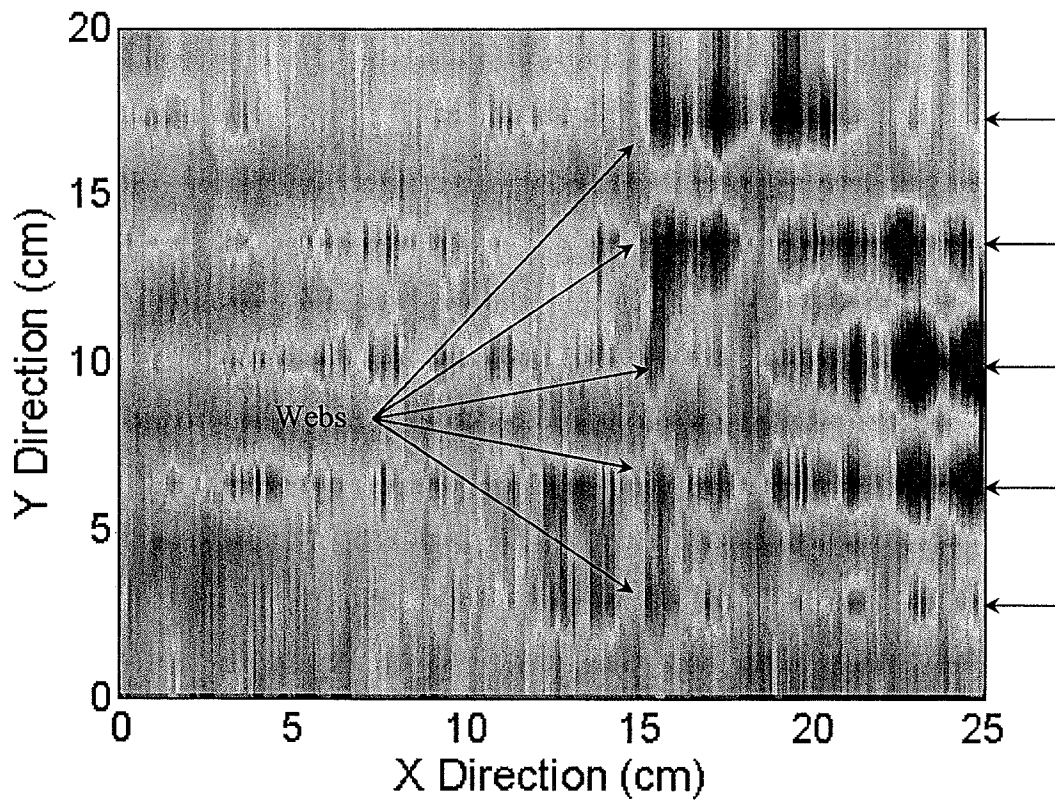


FIGURE 26. Real-Time Image of a Scanned Area on Multi-Layered FRP Composites

Figure 27 shows a scanned image of the FRP bridge deck (Specimen #4). No clear indication of voids/delaminations was found, but the webs (as shown by the read lines) inside of the structure were successfully detected. This test confirmed the ability of the smart array antenna prototype for inspecting pre-fabricated FRP structural members, as well as FRP-wrapped concrete members.



(a) Scanned Area



(a) Scanned Image

FIGURE 27 Scanned Image of an FRP Bridge Deck

4. PLANS FOR IMPLEMENTATION

Based on the success of this IDEA project, Newport Sensors, Inc. plans to commercialize the smart array antenna technology by product developing and marketing. The company has developed a preliminary design of a hand-held NDE device incorporating the smart array antenna technology for in-situ and real-time NDE inspection of concrete structures wrapped with FRP jackets, as shown in Figure 28.

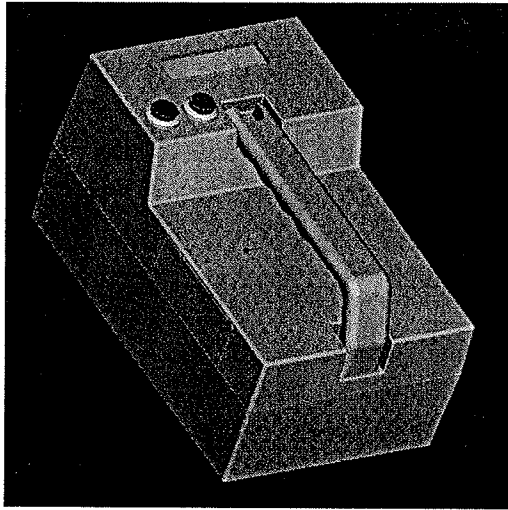


FIGURE 28 Future hand-held NDE product

Extensive field evaluation of the product will be performed at bridge sites where concrete bridge columns or superstructure members are strengthened/retrofitted with FRP jackets. Particular attention will be paid to evaluate the ability of our system to accommodate significant uncertainties involved in the materials and their surrounding environments (such as moisture).

Upon field evaluation and subsequent technology evaluation, commercial products will be developed and marketed. The primary market of the array antenna NDE product will be the bridge superstructures strengthened by FRP composite sheets. As truck loads start to increase on the nation's highway bridges in 2007, a substantial number of existing bridge superstructures will need to be strengthened, for which FRP is an excellent candidate. For this application, the quality of bonding between FRP and concrete is critical to the integrity of the structure. The company will take advantage of this opportunity to penetrate the market, by partnership with FRP suppliers, contractors, and inspectors, as well as bridge owners. In addition, the company plans to actively disseminate R&D results through journal publications, media releases, conference presentations, and exhibitions.

CONCLUSIONS

The IDEA funding enabled Newport Sensors, Inc., to explore an innovative smart array antenna technology for in-situ and real-time nondestructive evaluation of FRP-wrapped concrete structural members. Such a technology is needed for evaluating long-term conditions of FRP-rehabilitated concrete bridges, particularly internal damage concealed by the FRP wrapping, caused either by poor FRP installation workmanship, or a destructive event such as earthquakes.

The smart array developed in this project consists of multiple antenna elements actively controlled by sophisticated electronics and software. Damage targeted by the proposed technology at the present project includes debonds (air voids) between concrete and FRP wrapping, and debonds between layers of a multi-layered FRP composites. Such invisible damage (hidden under the FRP wrapping) is detected by illuminating the structure with microwaves from the antenna array and comparing the scattered microwave signals, received by the array, with a reference signal obtained at a point involving no damage on the same structure. The array can electronically scan a focused microwave beam through an area of eight square inches at a time in approximately one second. The novel wave focusing technique enables a high signal to noise ratio, a great inspection depth, and real-time damage assessment. Such high performance functions are beyond the capacities of existing NDE technologies and offer unique advantages for assessing internal damage in FRP or FRP-wrapped concrete structures.

In this project, technical requirements for the system were first developed based on extensive interview with potential users. Then technical specifications were determined and preliminary design developed based on simulation analysis. Finally a prototype array antenna system was developed by designing, fabricating, and integrating low-cost high-performance array antennas, sophisticated phase shifters, a compact power supply unit, a single board computer-based controller, together with a unique software package for controlling the wave focusing/phase shifting operations and processing received microwave signals. The system was then evaluated through extensive experimental studies on a variety of specimens of concrete and FRP composites. The following conclusions can be made from this study:

1. A knowledgebase was established in this project with respect to the unique application of microwaves for NDE of concrete and FRP structures. It was found that microwave in the 10GHz range is appropriate to use for NDE inspection of the interface between a concrete structure and its FRP wrap.
2. The feasibility of the proposed wave focusing technique based on phase shifting of array antenna was experimentally demonstrated, including the high speed, wave penetration depth, and spatial resolution.
3. An optimal configuration of the array antennas was developed based on the size of the focused beam (or the radiation pattern), the radiation power and the bandwidth.

4. It is critical to decouple interferences among different components in the antenna systems in order to increase the signal to noise ratio.
5. Based on extensive evaluation tests on concrete-FRP specimens involving debonds of various sizes in the interfaces between FRP and concrete, as well as between layers of a multi-layered FRP composites, the effectiveness of the smart array antenna system in detecting and quantifying the debonds was experimentally demonstrated.

Based on the success of this IDEA project, Newport Sensors, Inc. plans to further develop the smart array antenna technology into a hand-held device and market the products for real-time and in-situ NDE of FRP-wrapped concrete bridge structures. The company, however, will perform further study (involving extensive field evaluations) before the commercialization of the technology, to address technical issues that were beyond the scope of this IDEA project, such as how to determine the threshold value, how much the total debonding area versus the total bonding area would deteriorate the structural performance.

REFERENCES

- Feng, M.Q., De Flaviis, F., and Kim, Y.J. (2002). "Use of Microwaves for Damage Detection of FRP-Wrapped Concrete Structures". *Journal of Engineering Mechanics, ASCE*, Vol. 128, No. 2, pp. 172-183.
- Kak, A.C. and Slaney, M. (1988), *Principles of Computerized Tomographic Imaging*. The Institute of Electrical and Electronics Engineers, Inc., New York.
- Kim, Y. J., Jofre L., De Flaviis, F., and Feng, M. Q. (2003). "Microwave tomographic array for damage detection of civil engineering structures", *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 11.
- Kim, Y. J., Jofre, L., Feng, M. Q, and De Flaviis, F., (2004). "Microwave sub-surface imaging technology for damage detection", *Journal of Engineering Mechanics, ASCE*, Vol.130, No. 7, pp. 858-866.
- Loud, S. and Kliger, H., (2001), "Infrastructure Composites Report 2001", *Composite Worldwide*.
- Rhim, H. C., and Büyüköztürk, O., (2000), "Wideband Microwave Imaging of Concrete For Nondestructive Testing", *Journal of Structural Engineering, ASCE*, Vol. 126, No. 12, pp. 1451-1457.

