TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

IDEA Innovations Deserving Exploratory Analysis Project

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report of Investigation

IDEA PROGRAM FINAL REPORT

Contract NCHRP-ID043

The IDEA Program
Transportation Research Board
National Research Council

June, 1997—November, 1998

ROBOTIC SYSTEM FOR UNDERWATER BRIDGE INSPECTION AND SCOUR EVALUATION

Prepared by:
James E. DeVault, William B. Hudson,
Mustaque Hossain
Kansas State University, Manhattan, KS

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5th Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, http://www.nationalacademies.org/trb/idea)

TABLE OF CONTENTS

EXECUTIVE SUMMARY 4

IDEA PROJECT 6

INTRODUCTION 6

UNDERWATER BRIDGE INSPECTION 6

METHODS OF INSPECTION 6

Visual Inspection 6

Tactile Detection 7

Other Methods 7

Cleaning 7

ROBOTS AND ROVs 7

CONCEPT AND INNOVATION 8

THE EXPERIMENTAL SYSTEM 8

The System Concept 8

Early Work: Feasibility Exploration 9

INVESTIGATION 9

IMAGING TEST SYSTEM AND EXPERIMENTS 9

Description of the Imaging Test System 9

Experimental Procedure 10

Test Block 11

Video Tape 11

DESCRIPTION OF THE ROBOTIC APPARATUS 12

Mechanical Components 12

Electrical Components 13

Communication and Control Structure 15

PLANS FOR IMPLEMENTATION 15

- WORK IN PROGRESS 15
- FUTURE WORK 16
- SUMMARY OF ADVISORY COMMITTEE MEETING 16
- PRODUCT PAYOFF 17
- STATUS OF PRODUCT TRANSFER 18

CONCLUSIONS 18

INVESTIGATOR PROFILES 19

REFERENCES 19

EXECUTIVE SUMMARY

Under development is a semi-autonomous robotic system capable of providing underwater inspection of bridge substructures located in rivers and streams. The system will be capable of positioning a sensor platform in close proximity to underwater bridge support structures and of providing video or other sensory information to support evaluation and documentation of structural condition including scour.

Project activities were divided between the design and fabrication of a prototype robotic system, and an evaluation of the performance of an underwater video camera and lighting system in turbid water conditions.

Work began with an evaluation of the ability of an underwater video camera and high-intensity lighting system to provide images of a quality sufficient to support detection of structural damage at various levels of water turbidity. A test apparatus capable of positioning a video camera along a concrete test block containing several structural defects in an underwater environment of variable turbidity was developed. Digital camera images representing over two hundred experimental parameter variations have been recorded. This method of inspection and data collection was shown to be viable under conditions of low to moderate turbidity. The addition of a clear-water-bag to the camera apparatus has extended this capability to the higher turbidity conditions often encountered in rivers of this region.

An advisory team of regional experts was convened to evaluate the results of the video system testing and to discuss the design and application of the robotic system being developed. The video images were reviewed by the advisory team and found acceptable. Advice was received that has prompted both an increased emphasis on the detection and evaluation of scour and a simplification of the robotic apparatus.

The focus of our work is now on the design and fabrication of an improved robotic apparatus based on experience gained through previous research and three generations of prototype construction. Various configurations of mechanical apparatus have been constructed. Microcomputer-based control and communications hardware has been implemented and a basic user-interface to the system has been developed. These research efforts have resulted in a base-line apparatus capable of traversing a vertical concrete structure representative of typical bridge support columns. It is believed that the feasibility of this technical approach has been sufficiently demonstrated.

Autonomous local operation of the robot units in response to global operator commands will require significant additional engineering effort. This work will involve both computer simulation and the construction of small-scale robot models that will duplicate the essential functions of the system robots. These models will facilitate laboratory experimentation with alternative control structures and algorithms.

Once the mechanical fabrication difficulties associated with the robot mechanism have been solved, the remainder of the on-board control and communications electronics can be installed.

The final area of effort will include the completion and refinement of the user-interface. In addition to providing the operator with control of the robots and camera equipment, the windows-based software will provide graphical indication of robot position and orientation and full data-logging support.

Future efforts are expected to result in a working engineering prototype that will support commercialization of a product. The apparatus under development is a robust system that does not rely on high precision manufacturing techniques. It is felt that systems of robots based on the design principles used in the prototypes could be easily manufactured by small to medium sized companies without large expenditures for capital equipment or specialized personnel training. The commercial system is expected to be

1) Capable of deployment and operation on a bridge substructure in streams or rivers with strong currents and in a range of flow conditions including storm and flood.

2) Capable of providing visual inspection of the structure in turbid water and, if required, of cleaning the surface before inspection.

3) Operable by highway maintenance personnel.

4) Sufficiently rugged to withstand repeated use without extensive adjustment or maintenance.

5) Affordable by state agencies.

This low-cost, reliable, automated, video image-based underwater bridge inspection system will be beneficial for highway, railroad, turnpike, toll and bridge agencies. The system will have the potential to prevent catastrophic failures of bridges and will provide cost savings through improved preventative maintenance of infrastructure, and enhanced public safety.

The Kansas State University Research Foundation (KSURF) has obtained patent protection for all aspects of this system [1]. The Mid-America Commercialization Corporation (MACC) markets the technological property of the university and negotiates license agreements for the transfer and successful commercialization of the inventions. The MACC has reviewed this technology and sees significant commercialization potential. The MACC intends to play a major role in the effort to place this technology in the marketplace and is developing an appropriate commercialization strategy and plan.

IDEA PRODUCT

INTRODUCTION

The life of any bridge depends on the preservation of the physical integrity of both the superstructure and substructure; therefore, the implementation of an adequate inspection, maintenance, and repair program for the entire structure is essential. There are approximately 575,000 highway bridges in the nation's National Bridge Inventory. Of these, 85 percent are over streams or rivers making underwater inspection a necessary practice. The importance of this is supported by the 80 flood-related failures that occurred over a recent 3-year period [2].

The objective of this research is to develop an automated robotic system that will enable safe and cost-effective underwater inspection of bridge substructures.

UNDERWATER BRIDGE INSPECTION

Inspection of the underwater portions of bridge structures is different from that of the visible parts; the harsher environment affects the inspector's mobility, visibility, and limits such functions as cleaning and sampling. The individual performing underwater bridge inspection must have considerable knowledge of the proper use and care of diving equipment, safety requirements, communication techniques, and diving operations. The inspector must

(a) be capable of working under adverse conditions, such as deep, cold water and poor visibility;
(b) have comprehensive knowledge of the design and construction features of bridge substructures;
(c) properly interpret and report what is observed;
(d) be able to recognize any structural deficiency and assess its seriousness;
(e) be able to identify incipient problems so that preventive action can be taken.

Most state agencies have recognized that competent engineering inspections of underwater structural elements are essential and have assumed the responsibility for such underwater inspections. Either agency or contract personnel perform inspection. Many agencies require professional engineers who are also certified professional divers. The majority of agencies use commercial divers supervised by professional engineers [3].

The frequency of underwater inspection varies among state and federal transportation agencies [3]. Some agencies routinely inspect existing bridge substructures below the waterline; most of these agencies perform these inspections in conjunction with above-the-waterline inspections of the substructure and superstructure. Several agencies schedule inspections of specific structures only after major storm events or when there are indications of specific underwater problems. A swim-through is scheduled immediately after each major storm where structural problems are anticipated. In some cases, high currents preclude any inspection from being accomplished.

The level of inspection and the staffing for underwater inspection differ among the transportation agencies. The number of structures with major underwater substructure components is a factor in an agency's decision to use in-house or contract inspection. Some of the coastal-area states have staffed and trained their own underwater teams for both routine and emergency work. Other states depend on contract inspection for all underwater work. Disadvantages of contracted inspections include: (a) slow response time to emergency situations; (b) problems associated with bidding for engineering services and the possibility of new contracts each year; and (c) assignment of final responsibility for the engineering report of the inspection.

METHODS OF INSPECTION

Visual Inspection

Visual examination is the primary method used to inspect the underwater portions of a bridge. The most obvious limitation to visual inspection is water clarity. In many cases, bridges are built in generally turbid water in which the degree of visibility varies over a wide range. When turbidity is high, underwater visibility can be very low [3]. However, there is evidence that an intense light focused on the surface at a distance of approximately twelve inches will allow video in murky water [4].

Documentation of observations on videotape is standard practice in some underwater inspections. The types and capabilities of commercially available underwater television cameras are numerous. Cameras are designed to be hand-held or mounted on the diver's headgear. Video offers the advantage of real-time display to the surface and real-time quality control of the video image. There have been remarkable developments in the field of underwater filming [5].

Tactile Detection

As the substructures of many bridges are in turbid water that severely limits visibility, the diver must touch and feel to detect flaws, damage, or deterioration. Divers are capable of conducting inspection using only tactile methods in zero visibility, but it is difficult, if not impossible, to qualitatively assess this technique. The task is even more difficult in cold water, if there is a strong current, or if the structure is coated with marine deposits. Currently, tactile detection makes up 50% of all underwater inspection jobs due to limited visibility [3].

Other Methods

Currently, some more sophisticated instruments, including echo sounders and sonar imaging devices are available.

Echo sounders (specifically fathometers) are effective in checking scour in the streambed adjacent to a bridge. However, fathometers are not effective when used very close to the structure, as erroneous returns from the sub-structural elements or from accumulated debris are likely to occur. Undermining of piers or abutments cannot be adequately detected with an echo sounder. When undercutting or undermining is suspected, there is no substitute for visual inspection [3].

Sonar imaging has proven to be extremely useful in low visibility environments [3]. It also provides structural data over and above that which is attainable through video imaging alone, since sonar can "see" through silt and algae covering concrete surfaces. It is thought that the most comprehensive results can be achieved by combining both video and sonar technologies in a single inspection process, allowing the option of utilizing both depending on inspection requirements.

Cleaning

Cleaning the underwater portions of the bridge substructure to facilitate inspection and detection of deficiencies is often required [3]. The extent of the cleaning will depend on the type of inspection being made. Routine inspections, when there are no known defects, generally require only light cleaning in select areas, whereas detailed inspections may require complete cleaning of certain structural elements. Light cleaning is usually performed with a diver's knife or hand tools such as chipping hammers or scrapers. The cleaning of thick, hard deposits from large areas is best accomplished with power tools such as pneumatic or hydraulic-powered chippers, grinders, and brushes. Sand or water blasters can also be used under water [3].

ROBOTS AND ROVs

Remotely Operated Vehicles (ROVs) have proven their importance as an integral part of the marine industry. Offshore petroleum and salvage operations have increasingly relied on information supplied by ROV site investigations to aid in planning and execution of underwater tasks. Initially, ROV designs tended to be generic i.e. diverse applications were sought for a technology developed to provide general inspection and simple task performance capabilities. New designs are more task specific [5].

Some underwater environments, considered too dangerous or cost prohibitive for divers, were found to be accessible for ROVs. However, while the ROVs have proven to be useful for the oil industry, the inability of these systems to operate under strong currents in streams and rivers seriously limit their ability to do underwater inspection for bridges. Commercial examples of these systems cannot navigate in currents of more than four knots [6].

Robotic apparatus is currently being applied to the inspection and maintenance of such diverse constructs as boat docks, railroad bridges, large pipes, storage tanks, and cargo ships [7]. Traditional evaluation and maintenance techniques utilized in these situations are often either inadequate or not cost effective.

It is generally acknowledged that robotic inspection systems will have a wide potential market. This potential is being addresses by a rapidly growing service robot industry. At this time, however, no system is available that can be used for underwater bridge inspection.

Successful service robot applications currently include inspection and maintenance operations in arduous environments as well as such diverse activities as medical care, fire fighting, and military reconnaissance. Characteristics common to these applications include a non-technical human operator/client interface, task specificity, and a degree of autonomy [7]. The prototype underwater robotic inspection system described in this report represents a direct entry into this expanding market.

CONCEPT AND INNOVATION

THE EXPERIMENTAL SYSTEM

The System Concept

Under development is a semi-autonomous robotic system that is to carry a sensor platform (initially equipped with a video camera) into an underwater environment to detect deterioration or damage to bridge support columns and related substructure including scour. The system operator is provided with positional data and sensor information (video image) that can be verbally annotated while being recorded. Basic operational commands are initiated by portable computer keystrokes and transmitted to the underwater apparatus. More detailed control is accomplished automatically by onboard microprocessor-based controllers.

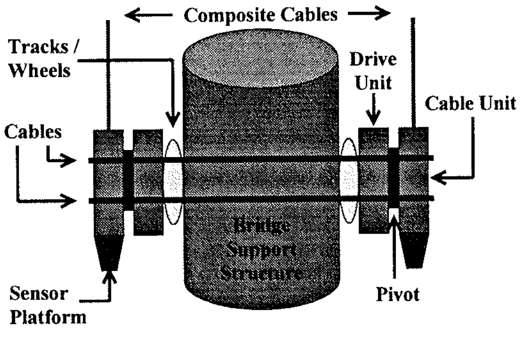

FIGURE 1 System Concept

The primary underwater apparatus consists of a team of two identical mobile robots designed to travel along opposite surfaces of the structure while connected to one another by a cable and winch system. Each robot contacts the surface through rubber tracks or wheels provided with cleats and driven by internal motors. Tensioning the cables that connect the two robots provides traction. The robots will be capable of both vertical and horizontal movement. While each robot operates its own drive motors and cable winches, coordination of movement and cable tensioning is provided automatically through transmission of feedback data between the robots and the control console. For larger structures, multiple robots may be evenly spaced around a support column requiring only the execution of a menu selection item in the operational software resident in the control computer.

Either robot may carry a video camera and a halogen light (or other sensors) and will position them approximately one foot from the surface under inspection. Auxiliary features may be provided such as a rotary scrubbing brush that can engaged and applied to the surface prior to filming. The use of cables for support of the robots would allow other testing systems to be fitted to the robots. It is possible that the robots could be outfitted for ultrasonic testing or core sampling if so desired. It is expected that this two robot pair, attached by cables, will be able to function effectively in highly turbulent waters.

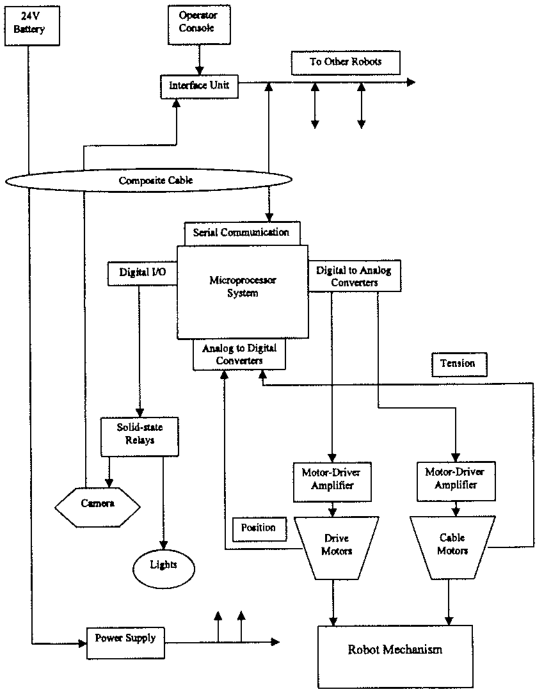

FIGURE 2 System Block Diagram

A compliant wheel located adjacent to the drive tracks and attached to a digital encoder will provide continuous positional data to the operator's console. An integral bumper will detect the bottom of the river or lake and can be used to establish a positional reference point. In addition, the robots will be equipped with a rolling sensor to detect any surface voids on the structure that occur between the robot's tracks or wheels.

Power and control signals are provided to each robot and video and data signals are returned to the control console through composite cables that also serve as emergency tethering and provide a means for lowering the robots into the water. The robots will be will be sealed to the environment.

Communication between the control console and the robots is will be accomplished using a serial data link. Single keystroke commands may be issued either to individual robots or to the robot team with inter-robot coordination being transparent to the operator. The graphical user interface will include display of positional data as well as indicators for such things as brush engagement, lights on or off, camera on or off, direction of motion, detection of bottom or end-of-travel, cable tension status, etc. Robots will be controlled using a simple, easily learned, set of commands.

Each robot will contain a microprocessor system that will receive and interpret operator commands and will sequence and control the on-board equipment. The coordination of movement and cable tension under all conditions of operation will be transparent to the operator.

Early Work: Feasibility Exploration

Preliminary work on this project was undertaken to explore the feasibility of employing a tethered team of robots in this application. A base-line apparatus capable of traversing a vertical concrete structure representative of typical bridge support columns was developed. Two identical robots were constructed and tested. No attempt was made to provide for underwater operation. Each robot consisted of a drive unit and a cable unit. The drive units incorporated rubber tracks fitted with cleats driven by geared servomotors, micro-controller boards, electronic interface boards, power amplifiers, and power supplies. The cable units included servomotor-driven cable spools and were free to pivot atop the drive units.

The robots responded to commands generated by a standard personal computer. Each command was interpreted by the robot-resident micro-controllers and appropriate assembly-language code was executed directly controlling the robot hardware. A rudimentary graphical user-interface to the system was developed. Through this interface, the robots could be individually or jointly commanded to move forward or backward and to turn either left or right. The user also had control of the tensioning of each of the two cables by which the robots attach themselves to the structure. The necessary coordination between robot motion and cable tensioning is accomplished manually and required substantial operator skill in the base-line system.

The system was powered from two automotive batteries. On-board power supplies generated all necessary operating voltages for the control electronics and sensors.

To allow convenient testing of the apparatus, a six-foot length of five-foot diameter concrete pipe was installed at the Kansas State University Manufacturing Learning Center (MLC). This test fixture was determined to be representative of the majority of bridge support structures to which this system might be applied. Initial testing identified the need for several mechanical modifications to the apparatus. In particular, it was found necessary to substantially reduce both the profile and the weight of the robot units. However, the system was successfully operated over the surface of the test structure both vertically and horizontally. Thus the feasibility of this approach has been sufficiently demonstrated.

The Advanced Manufacturing Institute of Kansas State University supported this work. The KSU Research Foundation filed for patent protection at that time and the investigators applied for external funding and support through the TRB IDEA Program.

INVESTIGATION

IMAGING TEST SYSTEM AND EXPERIMENTS

Description of the Imaging Test System

The experimental apparatus is mounted in a 1500-gallon polypropylene tank measuring eight feet in diameter and painted black to eliminate transmitted sunlight below the water surface. Centered in the tank is a 2' x 2' x 2' foot concrete block fabricated with specific defects on each of the four vertical surfaces. Also located in the tank are two submersible pumps and a manifold system constructed of PVC piping designed to provide the agitation necessary to keep soil components in suspension/mixture.

A consumer-grade digital camera (Hitachi model VM-H100LA) capable of underwater operation is mounted on a fixture which provides positioning of the camera at a continuously variable distance from

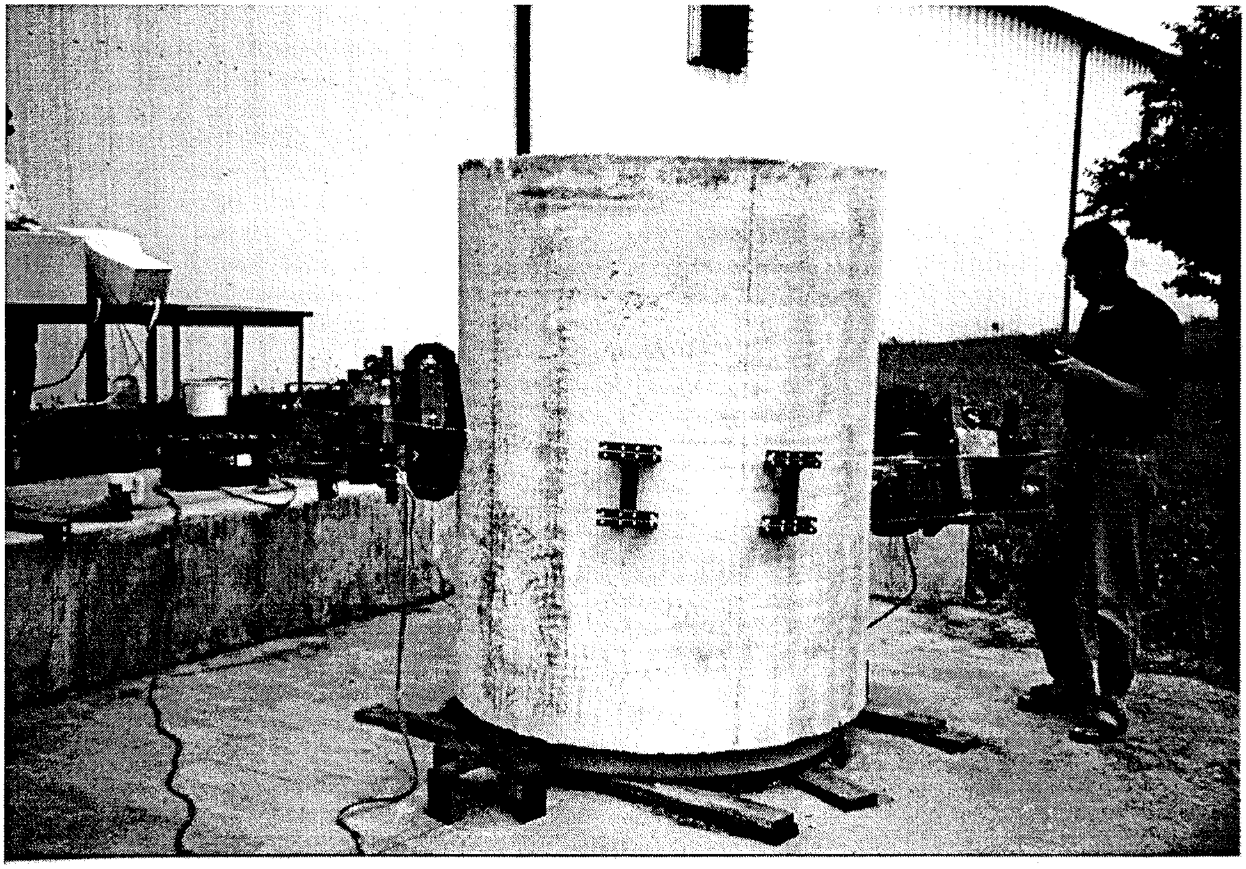

FIGURE 3 Early Prototype of the Robotic Inspection System

the test block surface. Application of this camera is subject to restrictions on depth and duration of submersion. The camera provides a remote viewer and control box and is mounted so as to allow rotation to each of the four sides of the test block. Also mounted on this fixture are two halogen automotive headlights that may be adjusted to illuminate the test block surface.

The entire apparatus is located on a concrete pad adjacent to the KSU Manufacturing Learning Center giving convenient access to electrical power, water, and drainage. Electrical distribution cables are provided with GFI protection. Turbidity measurements are made on-site using a DRT-100 research turbiditimeter manufactured by HF Scientific Inc. of Fort Meyer, FL.

Experimental Procedure

The camera was first positioned to view the particular test block face incorporating a specific fault. A sample of water near the camera was taken to measure turbidity. Images were obtained at distances at several distances from the block. An image was taken at the widest zoom level to get the maximum field of view and then at a longer focal length to make the fault fill the image. The maximum distance at which the fault could be visually detected was also determined. This was done by initially positioning the camera at the circumference of the tank (a distance at which the fault could not be seen at higher levels of turbidity), and then moving it toward the block until the fault could be discerned on the remote LCD screen of the camera. This distance from the block at which the image was first decipherable (qualitative judgement) was recorded. After these images were obtained, a second water sample was taken for turbidity measurement to ensure that the soil components remained in suspension/mixture throughout the test procedure.

This procedure was initially performed at low turbidity levels, and then repeated at incrementally higher levels. Each turbidity increment was achieved by adding soil and then allowing the agitation system to mix the contents for five minutes. Then the imaging procedure was repeated until test block fault became difficult to discern at the 2-inch distance.

The tank was then drained and the fixture rotated to view a different face on the test block.

Test Block

Figure 4 shows the 2' x 2' x 2' concrete block cast in the Concrete Laboratory at Kansas State University to simulate the scaled underwater bridge structure. A 6" x 6" window was formed in on one side of the form for the cube to expose a #5 rebar to simulate an exposed rebar in the bridge structure. Two grooves approximately 1/8" and 1/4" in width, were formed with a saw to simulate wide cracks. Finally, the block was struck with a sledgehammer to form several spalls of different depths.

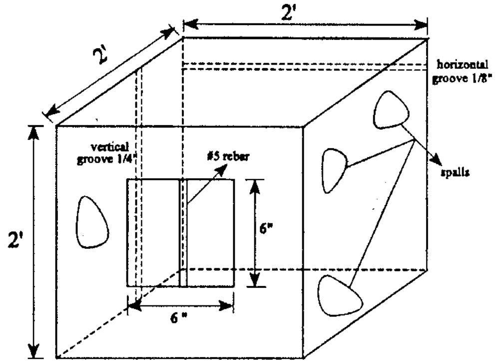

FIGURE 4 Concrete Test Block to Simulate Underwater Bridge Structure

Selection of Representative Turbidity Values for the Experiment

In order to duplicate the murkiness of water in the streams and rivers in the test barrel, historical turbidity data were collected at seven locations on four major rivers in Kansas. The Kansas Department of Health and Environment (KDHE) periodically samples water from the rivers and streams of Kansas and maintains a database of turbidity values [8]. The four rivers selected are the Arkansas, the Kansas, the Missouri and the Republic. Sampling stations were located on the upper and lower reaches of all rivers except Missouri. Table 1 shows the summary statistics of the turbidity data (NTU) at different locations. The readings show a wide variation. This is expected because the turbidity values depend on the run off. In general, the Missouri River in Kansas has the highest overall mean turbidity. However, the maximum turbidity was observed on Kansas River at Wamego in northeast Kansas. The Republican River in the upper part of the state and the Arkansas River in the southwest Kansas showed the lowest mean turbidity values. The minimum values indicate that sometimes the river water was very clean. For this experiment, it was decided to increase the turbidity of the water in the test-barrel from 1 (clear water) progressively upward. Underwater imaging was done up to a maximum turbidity value of approximately 60.

Note that this data includes a small number of measurements at extremely high turbidity levels. These data skew calculations of the mean and standard deviation. In discussions with various civil engineering professionals, we have concluded that turbidity levels of 0-60 NTU represent a more typical range of conditions.

Video Tape

Digital camera images representing over two hundred experimental parameter variations have been recorded on Hi8 format videotape. Turbidity levels, test block surfaces, and camera distances are identified verbally on the tape.

Additional experimentation with increased lighting intensity provided enhanced resolution of detail and better color discrimination at higher turbidity levels. The addition of a clear-water bag placed between the camera lens and the test block provided clear and detailed images at turbidity levels greater than 60 NTU. These images were judged to be fully satisfactory by an advisory team of bridge inspection experts. We believe that the substantial difficulty of incorporating a clear-water bag into the robotic apparatus has been resolved pending the fabrication and testing of an attachment described elsewhere in this report.

Location	Number	Mean	STD	Max.	Min.
Missouri R. at Kansas City	163	169	224	1080	2
Kansas R. at Kansas City	219	112	175	1090	5
Kansas R. at Wamego	217	87	157	1600	2
Republican R. near Hardy, Neb.	187	56	122	1100	2
Republican R. below Clay Center	42	56	129	800	1
Arkansas R. near Arkansas City	198	95	153	800	2
Arkansas R. near Great Bend	191	32	73	680	2

TABLE 1 Summary Statistics of the Turbidity Readings on Selected Kansas Rivers

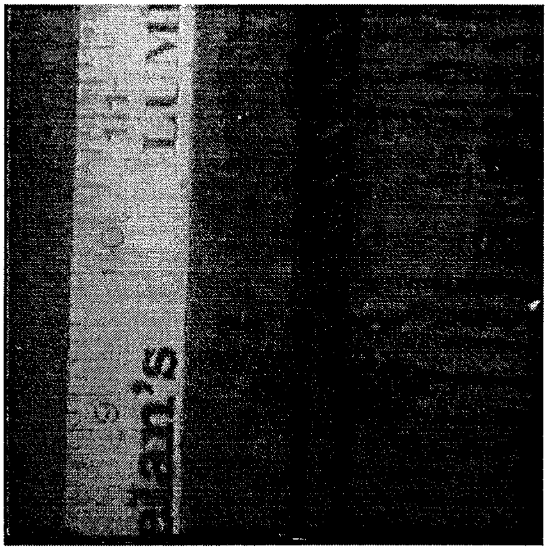

FIGURE 5 Camera image of exposed #5 rebar in water of 55 NTU turbidity using clear-water bag.

DESCRIPTION OF THE ROBOTIC APPARATUS

Mechanical Components

A two-robot system capable of submerged operation has been designed and constructed. Each robot includes two powered drive wheels and a pair of passive out-riggers that provide lateral support while channeling the tethering cables that hold the robots in contact with the bridge support structure [Figure 6].

The rectangular upper body of each robot provides space for the mounting of pulse-width modulated drive amplifiers for the motors, microprocessor board assemblies, power supplies, and sensor control relays. Initially, control of the motors was accomplished using a remote switch-box which operated optically coupled MOSFET H-bridges that switch the motors on and off while providing control of direction of rotation.

A motor-driven lead screw that drives a chain that simultaneously turns the two wheel hoop and motor assemblies provides steering. The wheels can be rotated through only slightly more than 90 degrees but may provide any required direction of robot travel by reversing direction of spin in conjunction with angular position.

The outriggers accommodate various structure dimensions as well as surface irregularities. They also act as guides for the cables that hold the robots to the structure. The motors and amplifiers that control cable tension are located within the body of the robot. The cable reels are driven through a worm gear that provides a braking function requiring that the motors be activated to either increase or decrease cable tension. Changes in cable tension are made in response to variations in drive-wheel motor torque demands.

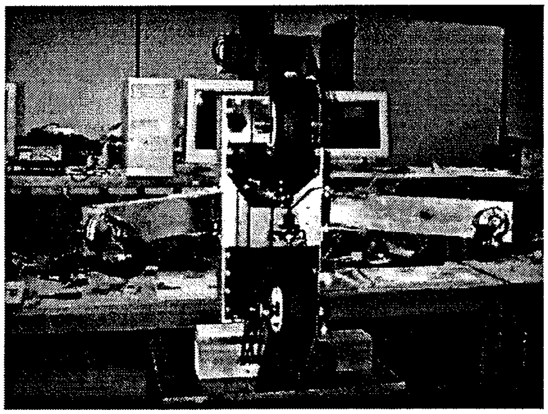

FIGURE 6 Second Generation Robot

The weight of each robot when fully equipped with on-board computers, motor-control amplifiers, and power supplies was intended to be less than sixty pounds. Instead, the weight of the final implementation is over one hundred pounds. Chassis construction is primarily of aluminum. It is expected that a commercial implementation of this system would incorporate an injection-molded plastic shell and that substantial effort would be made to reduce the weight to below forty pounds.

A method of incorporating a clear-water bag between the camera lens and the surface to be inspected while allowing travel along that surface has been conceived but not yet fully implemented. Briefly, the flexible, clear plastic bag is mounted in an accordion-like structure attached about the camera and terminating in one or more rollers that support the unit against the concrete surface while simultaneously providing tactile feedback information about the surface through a spring-loaded linear potentiometer. This allows the clear-water bag to track an irregular surface without rubbing against it directly. The output of the potentiometer can then be used to construct a surface profile.

Electrical Components

The microcomputers selected for this implementation are based on the AMD AMi88ES processor and are designed by Tern Inc. These 40MHz microcomputer board sets provide eleven channels of twelve-bit analog to digital conversion (ADC), six channels of twelve-bit digital to analog conversion (DAC), and thirty digital input/output (I/O) lines. Also provided are an LCD controller, a keypad interface, two RS-232 serial ports, eight comparator inputs, six solenoid drivers, and an on-board regulated power supply. The power supply provides all necessary operating voltages from a single +12-volt input voltage. Extensive use will be made of the ADCs and DACs to read sensor information and to provide control voltages for the amplifiers that drive the motors. The RS-232 serial ports will be used provide communication between robots as well as with the personal computer which serves as the operator's console.

We selected GALIL MSA-12-80 servo amplifiers to control the four drive motors and the two cable tensioning motors (the steering motors are driven separately in an on/off mode). These amplifiers utilize power MOSFETs and surface mount technology to produce high power in a small package weighing only 10 ounces. With an input of 24 volts, they provide 12 Amps continuous current and allow peaks of 25 Amps. The switching frequency for the pulse-width-modulated control is 33KHz. The amplifiers provide four-quadrant regenerative operation with adjustable loop gain, current limit, and offset. They are protected against over-voltage,

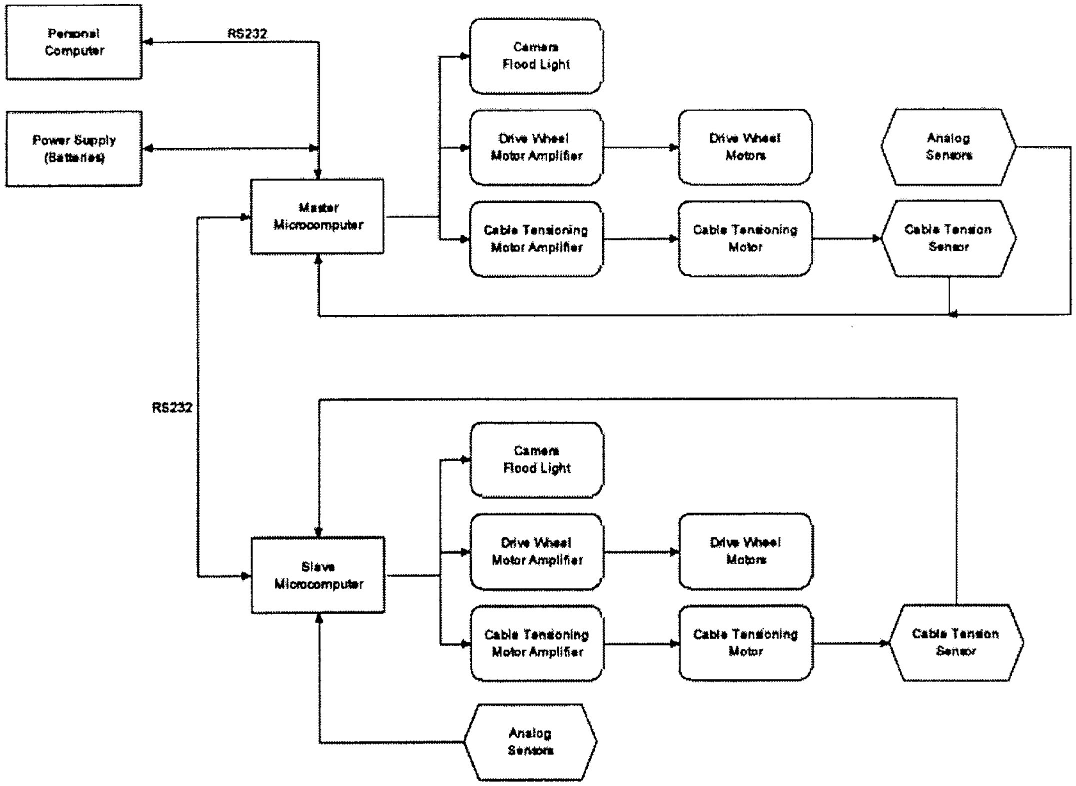

FIGURE 7 Electrical Control System

over-current, over-heating, and short circuits. Due to budget limitations, these amplifiers have not been purchased by this project but are on loan from a prior research project.

We selected Electro-Craft E552 DC motors to drive the four robot wheels. With a 180:1 gear-head attached, these motors provide 89 in-lb of torque at 28 rpm. An integral tachometer provides velocity feedback to the servo amplifier. The motors were purchased without shaft-position encoders due to budget limitations. Existing encoders from an earlier project will be mounted on these motors. The voltage operating range is from 0-28 volts with a locked-rotor current of 11.4 amps at 24 volts. Two earlier models of these motors available from another research project are used for cable tensioning. The motors are fitted with 12.5:1 gear-heads and also include integral tachometers. Shaft-position encoders are not required in this application. The cable winches are driven through a worm-gear system that provides a braking function as well as the required torque.

Pittman GM9413G912 DC motors with 127.7:1 gear-heads are used to drive the lead-screw to provide steering. While it was originally intended to servo these motors to support robot movement in any direction, feedback from our advisory committee meeting suggested that detection of surface irregularities was considered secondary to the detection of scour. We have consequently designed for operation in a mode providing vertical travel directly to the riverbed followed by circumnavigation of the support structure. This movement requires only that the steering motor provide +/-90 degree turning of the drive wheels. Thus these motors are driven from solid-state relays on an on-off basis.

Power for the robotic system is supplied by two 12 marine batteries connected in series for 24 volt operation. The motors used for locomotion, cable tensioning, and steering operate at 24 volts. The microprocessor system requires several lower voltage levels that are derived on board from a required 12-volt supply. We selected the POWER-ONE model DGP20XXT5/12 triple-output converter to be installed in each robot. These converters supply +5 volts at up to 2500mA and +/- 12 volts at up to 300mA from a 24-volt supply. These converters were selected for their small size and expected high-reliability in addition to meeting the functional requirements.

Communication and Control Structure

Remote computer control of the system through a graphical user-interface necessitates bi-directional communication with the individual robots that comprise the inspection system. Software has been developed to support a communication protocol capable of generating control commands and receiving sensor data on an effectively real time basis.

The electronic communication and control system for the bridge inspection robots consist of on-board microcomputers located within each robot and a remote operator's console (in the form of an augmented portable computer). Global command and control functions are initiated at the operator's console. The microcomputers are used to control motors, gather and react to sensor information, and communicate with the operator's console.

Each member of the robot team is identically constructed and is configured with duplicate resident software. However, at the time of deployment, one of the robots will be designated as the "master" and the second robot as a "slave". All communication between the operator's console and the robots is channeled through the master robot. The use of a master-slave configuration provides a significant simplification the communication protocol between the host computer and the robots.

The master robot receives global commands identifying the various tasks to be performed via an RS232 serial communications channel. This information is partitioned and translated into local parameters and instructions by the master robot software before transmission to the slave robot. During execution of these instructions, each robot provides local status information to the inter-robot communications channel.

Global operator commands requiring a change in position are expanded into a set of local motor commands for both master- and slave-robots. These commands are executed in an incremental fashion with continuous reference to status information providing coordination between robot movements as well as coordination with necessary changes in cable tension. Sensor control commands such as those required to operate the video camera and flood lights are interpreted by the master robot and either used by that robot or sent to the slave robot for execution as required. While sensor data such as the video signal may be transmitted directly to the operator's console, sensor status is channeled to the master robot where it is assembled into an information packet status packet prior to transmission to the operator.

PLANS FOR IMPLEMENTATION

WORK IN PROGRESS

Because the final size and weight of robots described above have precluded situated operation, a third-generation system of significantly different design has been developed. This system incorporates pneumatic motors on open frame aluminum structures. The control electronics are separately housed and remotely located so as to minimize the weight of the system. The robots are waterproof and are of a size and weight to allow deployment under expected operating conditions. This base-line system has been tested under manual control on our five-foot diameter concrete test pipe. While the operation of this apparatus is still somewhat awkward, the new approach shows much promise. The development of a commercially viable product will likely be based on this prototype.

A Gast Model 1UP-GR11 1/3 HP Air Gearmotor drives each robot. Torque is applied to a single drive-wheel through a dual chain and sprocket system resulting in an operating speed of approximately six inches per second under load. Steering is implemented in tricycle fashion by turning the drive-wheel with a separate air-cylinder through a lever-arm. Rear wheels are essentially casters. Outrigger arms guide a single tensioning cable. The robots can be made neutrally buoyant with individual air-bags inflatable by the pneumatic drive-system supply.

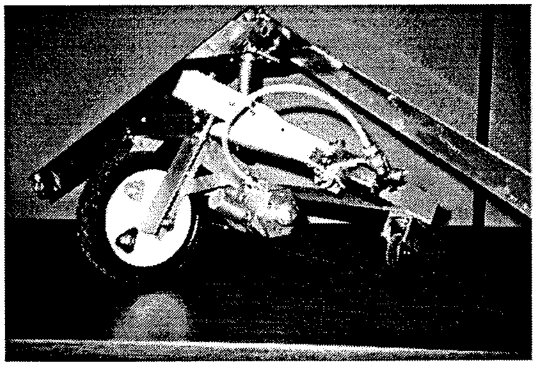

FIGURE 8 Third Generation Robot: View of Pneumatic Motor and Cylinder-Actuated Steering System

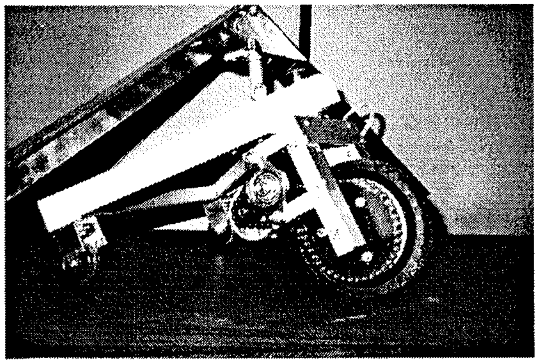

FIGURE 9 Third Generation Robot: View of Chain and Sprocket Drive System

FUTURE WORK

Autonomous local operation of the robot units in response to global operator commands will require significant additional engineering effort. This work will involve both computer simulation and the construction of small-scale robot models that will duplicate the essential functions of the system robots. These models will facilitate laboratory experimentation with alternative control structures and algorithms.

Once the mechanical fabrication difficulties associated with the robot mechanism have been solved, the remainder of the on-board control and communications electronics can be installed.

The final area of effort will include the completion and refinement of the user-interface. In addition to providing the operator with control of the robots and camera equipment, the windows-based software will provide graphical indication of robot position and orientation and full data-logging support.

SUMMARY OF ADVISORY COMMITTEE MEETING

An advisory meeting was held on October 17, 1997 for the purpose of describing our project, sharing the research results obtained to date, and soliciting advice as to the future direction, emphasis, and methodology of our work [9].

Significant results of this meeting included the strong advice that our emphasis should be on the detection of scour at the base of bridge substructures rather than on the detection of surface irregularities of the concrete above the river bed. It was generally agreed that many of the proposed features and capabilities of the system would be secondary to the scour detection function.

Our long-term response to this input will be to mount sonar equipment on the robot's sensor platform, initially oriented downward. The robot apparatus and controls will be optimized to accommodate vertical travel directly to the riverbed followed by a circumnavigation of the support structure while scanning the immediate area around the base. Our immediate response

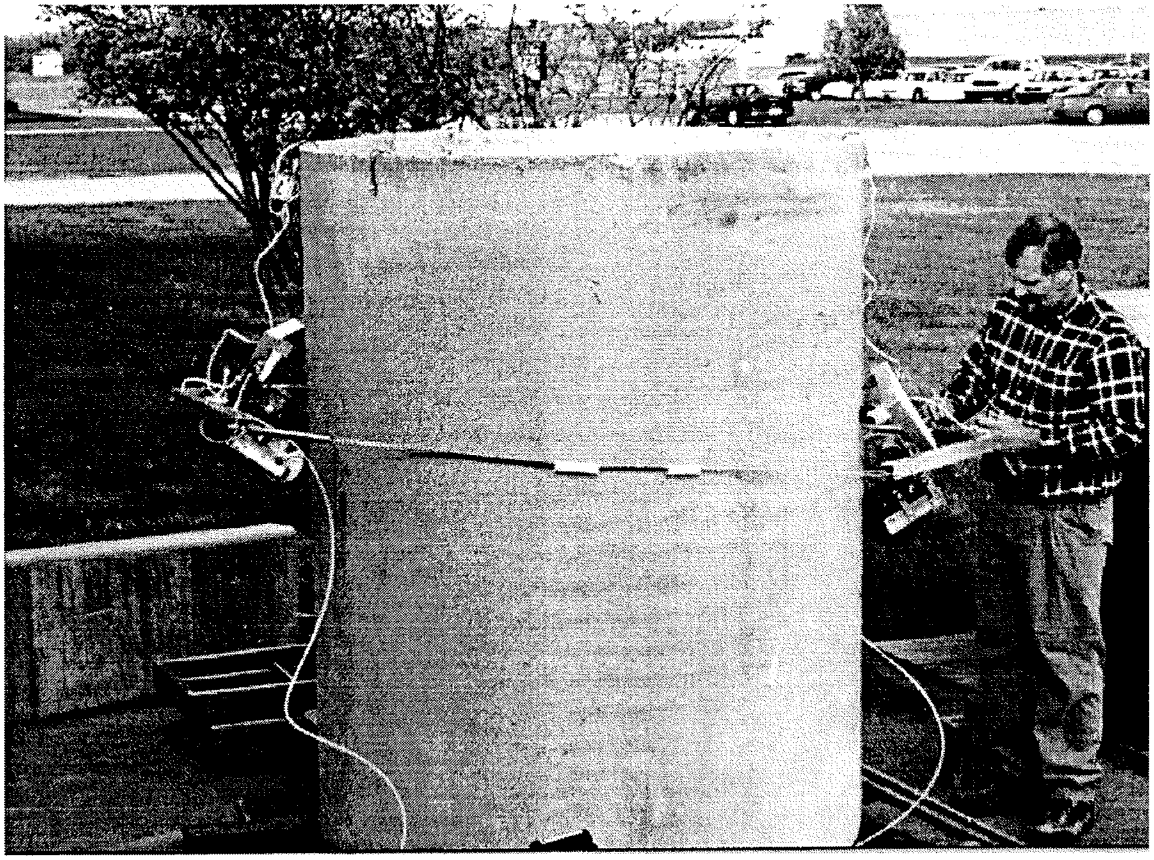

FIGURE 10 Robot System in Operation on Concrete Test Pipe

will be to complete the design of the system in a way that will be compatible with this application.

Operation exclusively in this mode would somewhat simplify the control of the robot system and, coincidentally, would be best served by the mechanical structure of the apparatus as presently constructed.

The underwater camera images gathered from the test-tank experiments were viewed and discussed. The difficulties with highly turbid conditions were as expected. The images recorded using the clear-water bags were judged to be fully adequate to the inspection process.

PRODUCT PAYOFF

This project is undertaken to explore the application of a robotic system to the inspection of bridge substructures. More generally, this invention relates to the positioning of multiple, linked robots on diverse structures such that they may undertake a variety of tasks. The robots may carry sensor platforms to support inspection and data collection or they may carry tooling to support painting or other maintenance and construction operations. Some features of this system contributing to a broad array of potential applications but also relating directly to this project are the following:

(a) Portable: can be easily transported to the inspection or maintenance site
(b) Non-destructive testing: does not require modification of existing structure.
(c) Reproducible Positioning: sensor platform supports detailed data collection.
(d) Unaffected by wind or water currents: deployable in rivers during floods or on towers during storms and will maintain contact with structure.
(e) Operation in inaccessible environments: provides inspection or maintenance in hazardous or challenging locations.
(f) Low cost: low cost relative to alternative solutions will allow rapid amortization of investment.
(g) Ease of operation: user interface provides operation from remote terminal with full feedback of system status.

Additional potential areas of application that may also be of interest to various governmental and commercial entities include:

(a) Pipelines
(b) Water towers
(c) Industrial smokestacks
(d) Nuclear cooling towers
(e) Oilrigs, oil derricks, floating platform support structures
(f) Docks

These applications may include maintenance such as painting as well as inspection.

Initial estimates of the manufactured cost of the system range from $25,000 to $50,000. A local dive shop, which has provided underwater bridge inspection services for over twenty-five years, charges $1,200 per hour of inspection. At this rate, the proposed system could be amortized in as few as thirty hours of operation.

Safety related issues such as the use of this system in hazardous environments and the reduction of inspection hours required of human divers provide additional justification.

STATUS OF PRODUCT TRANSFER

The expected outcome of this project is an engineering prototype of a bridge inspection system. This prototype will provide a basis for the development, manufacture, and commercialization of a new and useful product.

The Kansas State University Research Foundation (KSURF) has obtained patent protection for all aspects of this system. The Mid-America Commercialization Corporation (MACC) markets the technological property of the university and negotiates license agreements for the transfer and successful commercialization of the inventions. The MACC has reviewed this technology and sees significant commercialization potential. The MACC intends to play a major role in the effort to place this technology in the marketplace and is developing an appropriate commercialization strategy and plan.

CONCLUSIONS

The objective of this research is to develop a semi-autonomous robotic system capable of positioning a sensor platform in close proximity to underwater bridge support structures and of providing video information to support evaluation and documentation of structural condition including scour.

Project activities began with an evaluation of the ability of an underwater video camera and high-intensity lighting system to provide images of a quality sufficient to support detection of structural damage at various levels of water turbidity. A test apparatus capable of positioning a video camera along a concrete test block containing several structural defects in an underwater environment of variable turbidity. Digital camera images representing over two hundred experimental parameter variations have been recorded. This method of inspection and data collection was shown to be viable under conditions of low to moderate turbidity. The addition of a clear-water-bag to the camera apparatus has extended this capability to the higher turbidity conditions often encountered in rivers of this region. These images were reviewed by the advisory team and found acceptable.

An advisory team of regional experts was convened to evaluate the results of the video system testing and to discuss the design and application of the robotic system being developed. Advice was received that has prompted both an increased emphasis on the detection and evaluation of scour and a simplification of the robotic apparatus.

The emphasis of our work is now on the design and fabrication of an improved robotic apparatus based on experience gained through previous research and prototype construction. A third-generation robot system is now under construction. An in-river demonstration of the prototype system and an assessment of its potential for use in routine underwater bridge inspection are our final goals.

These research efforts have resulted in a base-line apparatus capable of traversing a vertical concrete structure representative of typical bridge support columns. It is believed that the feasibility of this technical approach has been sufficiently demonstrated.

Future efforts are expected to result in a working engineering prototype that will support commercialization of a product. The apparatus under development is a robust system that does not rely on high precision manufacturing techniques. It is felt that systems of robots based on the design principles used in the prototypes could be easily manufactured by small to medium sized companies without large expenditures for capital equipment or specialized personnel training. The commercial system is expected to be

1) Capable of deployment and operation on a bridge substructure in streams or rivers with strong currents and in a range of flow conditions including storm and flood.

2) Capable of providing visual inspection of the structure in turbid water and, if required, of cleaning the surface before inspection.

3) Operable by highway maintenance personnel.

4) Sufficiently rugged to withstand repeated use without extensive adjustment or maintenance.

5) Affordable by state agencies.

This low-cost, reliable, automated, video image-based underwater bridge inspection system will be beneficial for highway, railroad, turnpike, toll and bridge agencies. The system will have the potential to prevent catastrophic failures of bridges and will provide cost savings through improved preventative maintenance of infrastructure, and enhanced public safety.

INVESTIGATOR PROFILES

James E. DeVault is Professor of Electrical and Computer Engineering at Kansas State University. His areas of specialization include mobile autonomous robotics, power and control electronics, industrial control systems, and instrumentation.

William B. Hudson is Associate Professor of Electrical and Computer Engineering at Kansas State University. His areas of specialization include neural networks, instrumentation, microprocessor design, and rehabilitation engineering.

Mustaque Hossain is Associate Professor of Civil Engineering at Kansas State University. Dr. Hossain has worked for four years with the Arizona Transportation Research Center (ATRC) of Arizona Department of Transportation (ADOT). His areas of expertise are pavement design, performance, non-destructive evaluation, and pavement materials.

REFERENCES

[1] DeVault, Hudson, Hossain, U.S. Patent Application S/N 08/869,497: ROBOTIC INSPECTION APPARATUS AND METHOD, Notice of Allowance issued September 17, 1998.

[2] NCHRP Project No.: 22- 04, 1993. Underwater Bridge Maintenance and Repair, Problem Statement.

[3] Lamberton, H.C., Jr., Sainz, Alfredo J., Crawford, Robert A., Ogletree, William B., Gunn, James E., Underwater Inspection and Repair of Bridge Substructures: National Cooperative Highway Research Program Synthesis of Highway Practice #88, 1981.

[4] Skinner, Robert, HNTB Corp., Kansas City, MO, April 1994. Personal Communication with M. Hossain

[5] Assoc. of Diving Contractors. Underwater, Vol. VI, No. 2, Spring, 1994.

[6] JW Fishers Mfg., Inc., Berkley, MA., Product Literature.

[7] Asami, Shuji, "Robots in Japan: Present and Future", IEEE Robotics and Automation Magazine, Vol. I, No. 2, June 1994.

[8] Kansas Department of Health and Environment, Environmental Protection Agency STORET System Database, May 1997.

[9] NCHRP-IDEA 43 Project Advisory Committee:

The following five regional experts were the primary participants in our meeting (October 1997):

Don Whisler, Bridge Inspection Engineer,
Kansas Department of Transportation.

Jim Murray, Division Engineer,
Missouri Department of Transportation.

Dave Meggers, Research Development Engineer,
Kansas Department of Transportation.

Danny Mahnke, Manager of Special Services,
HNTB Corporation.

Dan Scherschligt, Bridge Management Engineer,
Kansas Department of Transportation

Also in attendance were the following people having interest in the project with regard to patent protection, commercialization, and manufacture:

Ron Trewyn, President,
Kansas State University Research Foundation

Ron Sampson, President,
Mid-America Commercialization Corporation

Diane Gorder, Vice President,
Mid-America Commercialization Corporation

David McLachlan, Associate Director,
Advanced Manufacturing Institute, KSU

Jeff Tucker, Operations Manager,
Manufacturing Learning Center, KSU

Dr. Inam Jawed of the Transportation Research Board IDEA Program was also present at the meeting.