Alternatives FOR LANDMINE DETECTION

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Prepared for the Office of Science and Technology Policy

The research described in this report was conducted by RAND's Science and Technology Policy Institute for the Office of Science and Technology Policy.

Library of Congress Cataloging-in-Publication Data

MacDonald, Jacqueline/
Alternatives for landmine detection / Jacqueline MacDonald, J.R. Lockwood.
p. cm.
Includes bibliographical references.
"MR-1608."
ISBN 0-8330-3301-8 (pbk.)
1. Land mines. 2. Explosives—Detection. I. Lockwood, J. R. II. Rand Corporation. III.Title.

UG490 .M337 2003
623' .26—dc21
2002155750

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Published 2003 by RAND
1700 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
1200 South Hayes Street, Arlington, VA 22202-5050
201 North Craig Street, Suite 202, Pittsburgh, PA 15213-1516
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PREFACE

This report assesses the potential for innovative mine detection technologies to speed clearance of the 45–50 million landmines around the world. The Office of Science and Technology Policy commissioned the report because of concerns about the slow pace of humanitarian demining.

Numerous studies have compared and evaluated the performance of mine detection technologies—those currently fielded and those under development. This report is unique because it focuses entirely on close-in detection of antipersonnel mines and leverages expertise of two groups of prominent experts including (1) specialists on the cutting edge of the latest technologies and (2) researchers and program managers with long-standing and broad experience in mine detection. Those in the first group wrote background papers describing the most recent research on each innovative detection technology; these papers are included in the appendixes of this report. Those in the second group (who are listed as coauthors of this report) reviewed the background papers and assessed the relative potential of the different technologies. The main report synthesizes the conclusions of this expert group as well as the results of the Science and Technology Policy Institute's (S&TPI's) review of mine detection literature.

The main report of this book was written to be accessible to a wide audience, including federal policymakers, the science community, nongovernmental organizations involved in humanitarian demining, and the general public. The appendixes provide additional technical details on specific mine detection technologies and will be of interest primarily to the science community. RAND is grateful to the authors and the corporate, academic, and governmental groups that allowed us to reproduce this important work in our study.

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Originally created by Congress in 1991 as the Critical Technologies Institute and renamed in 1998, the Science and Technology Policy Institute is a federally funded research and development center sponsored by the National Science Foundation and managed by RAND. The institute's mission is to help improve public policy by conducting objective, independent research and analysis on policy issues that involve science and technology. To this end, the institute

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- helps science and technology decisionmakers understand the likely consequences of their decisions and choose among alternative policies; and
- helps improve understanding in both the public and private sectors of the ways in which science and technology can better serve national objectives.

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SUMMARY

Antipersonnel mines remain a significant international threat to civilians despite recent intense efforts by the United States, other developed countries, and humanitarian aid organizations to clear them from postconflict regions. Mines claim an estimated 15,000–20,000 victims per year in some 90 countries. They jeopardize the resumption of normal activities—from subsistence farming to commercial enterprise—long after periods of conflict have ceased. For example, in Afghanistan during 2000, mines claimed 150–300 victims per month, half of them children. Although most of these mines were emplaced during the Soviet occupation of Afghanistan (from 1979 to 1988), they continue to pose a serious risk to returning refugees and have placed vast tracts of farmland off limits. The United States currently invests about $100 million annually in humanitarian mine clearance—the largest commitment of any country. Despite this investment and the funding from many other developed nations and nongovernmental organizations, at the current rate clearing all existing mines could take 450–500 years.

This report addresses the following questions:

- What innovative research and development (R&D) is being conducted to improve antipersonnel mine detection capabilities?
- What is the potential for each innovative technology to improve the speed and safety of humanitarian demining?
- What are the barriers to completing development of innovative technologies?

- What funding would be required, and what are the options for federal investments to foster development of promising mine detection technologies?

We focus on close-in detection of antipersonnel mines rather than on airborne or other remote systems for identifying minefields.

The report was written by RAND S&TPI staff and a task force of eight experts in mine detection from universities and U.S. and Canadian government agencies. In addition, 23 scientists provided background papers with details on specific mine detection technologies; these papers are published in this report as separate appendixes.

LIMITATIONS OF CONVENTIONAL MINE DETECTION TECHNOLOGIES

The tools available to mine detection teams today largely resemble those used during World War II. A deminer is equipped with a handheld metal detector and a prodding device, such as a pointed stick or screwdriver. The demining crew first clears a mined area of vegetation and then divides it into lanes of about a meter wide. A deminer then slowly advances down each lane while swinging the metal detector low to the ground. When the detector signals the presence of an anomaly, a second deminer probes the suspected area to determine whether it contains a buried mine.

The overwhelming limitation of the conventional process is that the metal detector finds every piece of metal scrap, without providing information about whether the item is indeed a mine. For example, of approximately 200 million items excavated during humanitarian demining in Cambodia between 1992 and 1998, only about 500,000 items (less than 0.3 percent) were antipersonnel mines or other explosive devices. The large number of false alarms makes humanitarian mine detection a slow, dangerous, and expensive process. Every buried item signaled by the detector must be investigated manually. Prodding with too much force, or failure to confirm the presence of a mine during probing, can lead to serious injury or death. Adjusting a conventional detector to reduce the false alarm rate results in a simultaneous decrease in the probability of finding a mine, meaning more mines will be left behind when the demining operation is completed. For humanitarian demining, trading off reductions in false alarms for reductions in the likelihood of finding buried mines is unacceptable.

CAPABILITIES OF INNOVATIVE MINE DETECTION TECHNOLOGIES

Research is under way to develop new detection methods that search for characteristics other than metal content. The aim of these methods is to substantially reduce the false alarm rate while maintaining a high probability of detection, thereby saving time and reducing the chance of injury to the deminer. Table S.1 summarizes these methods. The second column indicates the detection principle on which each is based. The remaining columns summarize the strengths, limitations, and performance potential of each. Chapter Two and the appendixes provide detailed reviews of each technology.

As shown in Table S.1, no single mine detection technology can operate effectively against all mine types in all settings. For example, nuclear quadrupole resonance can find mines containing the explosive cyclotrimethylenenitramine (known as royal demolition explosive [RDX]) relatively quickly, but it is slow in confirming the presence of trinitrotoluene (TNT). Acoustic mine detection systems have demonstrated very low false alarm rates, but they cannot find mines buried at depths greater than about one mine diameter. Chemical vapor sensors can find plastic mines in moist soils, but they have difficulty locating metal mines in dry environments.

Given the limitations of individual sensor technologies, major breakthroughs in mine detection capability are likely to occur only with the development of a multisensor system. The multisensor system we envision would combine two or more of the technologies listed as “promising” in Table S.1 and would leverage advanced algorithms that would process the raw signals in concert to determine whether they are consistent with known mine characteristics. Rather than bringing together two commercially available technologies to form the combined sensor platform, the technology optimization and integration would occur at the design stage, and the development of

Table S.1

Summary of the Detection Technologies Reviewed

Technology	Operating Principle	Strengths	Limitations	Potential for Humanitarian Mine Detection
Electromagnetic				
Electromagnetic induction	Induces electric currents in metal components of mine	Performs in a range of environments	Metal clutter; low-metal mines	Established technology
Ground-penetrating radar	Reflects radio waves off mine/soil interface	Detects all anomalies, even if nonmetal	Roots, rocks, water pockets, other natural clutter; extremely moist or dry environments	Established technology
Electrical impedance tomography	Determines electrical conductivity distribution	Detects all anomalies, even if nonmetal	Dry environments; can detonate mine	Unlikely to yield major gains
X-ray backscatter	Images buried objects with x rays	Advanced imaging ability	Slow; emits radiation	Unlikely to yield major gains
Infrared/hyperspectral	Assesses temperature, light reflectance differences	Operates from safe standoff distances and scans wide areas quickly	Cannot locate individual mines	Not suitable for close-in detection
Acoustic/Seismic	Reflects sound or seismic waves off mines	Low false alarm rate; not reliant on electromagnetic properties	Deep mines; vegetation cover; frozen ground	Promising

Table S.1—continued

Technology	Operating Principle	Strengths	Limitations	Potential for Humanitarian Mine Detection
Explosive Vapor				
Biological (dogs, bees, bacteria)	Living organisms detect explosive vapors	Confirms presence of explosives	Dry environments	Basic research needed to determine potential (though dogs are widely used)
Fluorescent	Measures changes in polymer fluorescence in presence of explosive vapors	Confirms presence of explosives	Dry environments	Basic research needed to determine operational potential
Electrochemical	Measures changes in polymer electrical resistance upon exposure to explosive vapors	Confirms presence of explosives	Dry environments	Basic research needed to determine whether detection limit can be reduced
Piezoelectric	Measures shift in resonant frequency of various materials upon exposure to explosive vapors	Confirms presence of explosives	Dry environments	Basic research needed to determine whether detection limit can be reduced
Spectroscopic	Analyzes spectral response of sample	Confirms presence of explosives	Dry environments	Basic research needed to determine whether detection limit can be reduced

Table S.1—continued

Technology	Operating Principle	Strengths	Limitations	Potential for Humanitarian Mine Detection
Bulk Explosives				
Nuclear quadrupole resonance	Induces radio frequency pulse that causes the chemical bonds in explosives to resonate	Identifies bulk explosives	TNT; liquid explosives; radio frequency interference; quartz-bearing and magnetic soils	Promising
Neutron	Induces radiation emissions from the atomic nuclei in explosives	Identifies the elemental content of bulk explosives	Not specific to explosives molecule; moist soil; ground-surface fluctuations	Unlikely to yield major gains
Advanced Prodders/ Probes	Provide feedback about nature of probed object and amount of force applied by probe	Could deploy almost any type of detection method	Hard ground, roots, rocks; requires physical contact with mine	Promising

algorithms for advanced signal processing would be an integral part of the process. The result would be a single, highly sensitive, and performance-optimized detection system that provides one specific signal to the operator. The Army countermine program currently is developing a dual-sensor system that combines separate electromagnetic induction (EMI) and ground-penetrating radar (GPR) technologies as part of a single operational platform known as the Handheld Standoff Mine Detection System (HSTAMIDS). However, HSTAMIDS does not use advanced signal processing. Rather, the operator receives two separate outputs: one from the EMI device and one from the GPR. This dual-sensor system does not make optimal use of the totality of information available from the combined sensors.

Advances in signal processing and understanding of single-sensor systems make the development of a multisensor system with a single signal possible in principle. Preliminary research has shown the potential for multisensor systems to reduce the number of false alarms by as much as a factor of 12. However, additional research is needed to establish a comprehensive technical basis for the design of such a system. Based on the time and costs required to create HSTAMIDS ($73 million over 15 years), we estimate that the new multisensor system would require a total investment of $135 million. Currently, the United States is not funding the necessary research. In 2002, the United States invested $2.7 million for close-in mine detection R&D for humanitarian demining. Of this amount, nearly $2.0 million went to making incremental improvements to existing EMI and GPR systems, and the rest funded research on explosive chemical vapor detection systems. No funding was allocated toward research that would lead to the development of an integrated multisensor system for humanitarian demining.

At the outset of this project, the Office of Science and Technology Policy asked RAND S&TPI whether development of an innovative mine detection system could enable mine clearance to advance 10 times faster than is currently possible. A multisensor system could reduce the false alarm rate by a factor of 10 or more. However, gains in mine clearance speed are not directly proportional to reductions in the false alarm rate because a substantial portion of the total clearance time is spent on site preparation activities, such as vegetation clearance. Very limited research has been conducted to date to analyze actual mine clearance data for determining what gains are theoretically possible with improved detection systems. The existing, limited research predicts that a system that eliminated 99 percent of false alarms would improve overall clearance rates by 60–300 percent of current rates, depending on the amount of vegetation present. Such gains would save billions to tens of billions of dollars in the total cost expected to clear all mines and would spare a large number of deminer and civilian lives. Pursuing development of an advanced multisensor system is worthwhile, even if order-of-magnitude decreases in clearance time are not possible with improved detection technology alone.

RECOMMENDATION: INITIATE AN R&D PROGRAM TO DEVELOP A MULTISENSOR SYSTEM

We recommend that the federal government undertake an R&D effort to develop a multisensor mine detection system. The first step in developing the program should be a short, preliminary study (costing less than $1 million) to consolidate existing theoretical and empirical research related to multisensor systems and signal processing. This preliminary study would be used to develop a blueprint for the R&D needed to produce a prototype system. We estimate that initial prototype development would cost approximately $60 million. The program should address the following four broad areas:

- algorithmic fusion of data from individual sensors (to develop the theory necessary to support an advanced multisensor system), funded at approximately $2.0–3.2 million per year;
- integration of component technologies (to address system engineering issues associated with combining multiple sensors as part of a single-sensor platform), funded at approximately $1.25–2.00 million per year;
- methods for detecting the chemical components of explosives (to further develop components of the multisensor system that would search for explosives rather than for the mine casing and mechanical components), supported at approximately $2.5–4.0 million per year; and

- techniques for modeling how soil conditions in the shallow subsurface environment affect various mine sensors (to allow predictions of integrated sensor system performance across the broad range of natural environments in which mines occur), funded at $500,000–800,000 per year.

Depending on the amount of resources invested in this research, a prototype multisensor system could be available within seven years. Once the prototype is developed, additional allocations totaling approximately $135 million will be needed to fund the engineering and development of an optimal, deployable system.

The benefits of a program to develop an advanced, multisensor system would include more rapid capability to help restore stability to postconflict regions, such as Afghanistan; more mines cleared per U.S. dollar spent on humanitarian demining; fewer deminer and civilian casualties; and utility to military countermine operations. In addition, the results of R&D on advanced signal processing and sensor fusion would be transferable to other applications in environmental, geophysical, medical, and other sciences.

ABBREVIATIONS

2ADNT	2-amino-4,6-dinitrotuluene
4ADNT	4-amino-2,6-dinitrotuluene
A/S	Acoustic-to-seismic
AFRL	Air Force Research Laboratory
AP	Antipersonnel
APG	Aberdeen Proving Ground
ARO	Army Research Office
AS&E	American Science and Engineering Inc.
ASTAMIDS	Airborne Standoff Minefield Detection System
AT	Antitank
BTI	Bubble Technology Industries
CBI	Compton backscatter imaging
CCMAT	Canadian Centre for Mine Action Technologies
CECOM	Communications-Electronics Command
CMAC	Cambodian Mine Action Centre
COBRA	Coastal Battlefield Reconnaissance and Analysis
CompB	Composition B
COTS	Commercial-off-the-shelf

CSS	Coastal Systems Station
CW	Continuous wave
DARPA	Defense Advanced Research Projects Agency
DC	Direct current
DERA	Defence Evaluation and Research Agency
DNT	Dinitrotoluene
DoD	U.S. Department of Defense
DRDC	Defence R&D Canada
DRES	Defence Research Establishment–Suffield
EIT	Electrical impedance tomography
EM	Electromagnetic
EMI	Electromagnetic induction
EO	Electro-optical
ERDC-CRREL	Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (U.S. Army)
FA	False alarm
FAA	Federal Aviation Administration
FAR	False alarm rate
FNA	Fast neutron analysis
G	Gauss
GHz	Gigahertz
GICHD	Geneva International Centre for Humanitarian Demining
GPR	Ground-penetrating radar
GPSAR	Ground-penetrating synthetic aperture radar
GSTAMIDS	Ground Standoff Mine Detection System
HD	Humanitarian demining

HMM	Hidden Markov model
HMX	Cyclotetramethylenetetranitramine
HPM	High-power microwave
HS	Hyperspectral
HSTAMIDS	Handheld Standoff Mine Detection System
ICBL	International Campaign to Ban Landmines
IDA	Institute for Defense Analyses
ILDP	Improved Landmine Detector Program
IPPTC	International Pilot Project for Technology Cooperation
IR	Infrared
JUXOCO	Joint Unexploded Ordnance Coordination Office
keV	Kilo-electron volt
kHz	Kilohertz
kVp	Kilovolt peak
kG	Kilogauss
LAMD	Lightweight Airborne Minefield Detection
LDV	Laser Doppler vibrometer
LED	Light-emitting diode
LM	Low metallic
LMR	Lateral migration radiography
LWIR	Long-wave infrared
μm	Micrometer
mA	Milliamp
MDD	Mine dog detection
MeV	Mega-electron volt

MHz	Megahertz
MLP	Multilayer perception
MMDS	Microbial Mine Detection System
MRI	Magnetic resonance imaging
mS	MilliSiemens
MURI	Multidisciplinary University Research Initiative
MWIR	Mid-wave infrared
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCPA	National Center for Physical Acoustics
NIR	Near infrared
NMR	Nuclear magnetic resonance
NQR	Nuclear quadrupole resonance
NRL	Naval Research Laboratory
NVESD	Night Vision and Electronic Sensors Directorate (U.S. Army)
ORNL	Oak Ridge National Laboratories
OSTP	Office of Science and Technology Policy
PCMCIA	Personal Computer Memory Card International Association
PD	Probability of detection
PFA	Probability of false alarm
PIN	Positive-intrinsic-negative
PM	Photo-multiplier
ppb	Parts per billion
ppq	Parts per quadrillion
ppm	Parts per million

ppt	Parts per trillion
PY	Person year
QM	Quantum Magnetics
R&D	Research and development
RDX	Royal demolition explosive [Cyclotrimethylenenitramine]
REMIDS	Remote Minefield Detection System
REST	Remote Explosive Scent Tracing
RF	Radio frequency
RFI	Radio frequency interference
ROC	Receiver operating characteristic
ROM	Rough order of magnitude
rpm	Revolutions per minute
S&TPI	Science and Technology Policy Institute
SAR	Synthetic aperture radar
SCR	Signal-to-clutter ratio
SERRS	Surface Enhanced Resonance Raman Spectroscopy
SIT	Stevens Institute of Technology
SNL	Sandia National Laboratories
SNR	Signal-to-noise ratio
SPIE	International Society for Optical Engineering
STAMIDS	Standoff Minefield Detection System
SWIR	Short-wave infrared
SwRI	Southwest Research Institute
T	Tesla
TNA	Thermal neutron analysis

TNO	Netherlands Organisation for Applied Scientific Research
TNT	Trinitrotoluene
TOF	Time of flight
UF	University of Florida
UHF	Ultra-high frequency
UM	University of Montana
UN	United Nations
UWB	Ultra-wide band
UXO	Unexploded ordnance
VMMD	Vehicle-Mounted Mine Detector
VNIR	Visible/near infrared
WES	Waterways Experimental Station
XMIS	X-ray mine imaging system