New Model
to Evaluate Weapon Effects
and Platform Vulnerability: AJEM

By Thomas L. Wasmund
Naval Surface Warfare Center, Dahlgren Division

The Advanced Joint Effectiveness Model (AJEM) gives both the platform vulnerability/survivability analyst and the munition lethality/effectiveness analyst a new tool with new capabilities that can provide more realistic estimates of weapon effects against platforms. AJEM can be used to evaluate all conventional ballistic threats against aircraft, missile, and ground-mobile targets. It is planned to be the Department of Defense (DoD) standard computer simulation for evaluating the lethality and terminal effectiveness of munitions and the vulnerability of aircraft, missiles, and ground systems. AJEM can be used during all phases of weapon system acquisition from research, design, and development to production, test, and evaluation.

AJEM has been jointly developed, and is continuing to be supported, by the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME), the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), and the U.S. Army Research Laboratory Survivability/Lethality Analysis Directorate (ARL/SLAD). Model development is leveraging years of effort by all three Services and the JTCGs, and incorporates and improves upon the capabilities of older models.

AJEM combines the elements of target geometric modeling, threat modeling, weapon-target encounter geometries and kinematics, proximity or contact fuzing, and damage mechanism/target interaction (penetration, fire, blast, etc.) to determine weapon effects on target components. This is combined with an evaluation of target system relationships (functionality, redundancies, etc.) to determine target remaining capability or loss of function/defeat.

AJEM’s software structure consists of three separate modules. Each module is distinct and runs as a separate process in a UNIX environment. These modules are:

- The Graphical User Interface,
- The Encounter Module, and
- The Vulnerability/Lethality (V/L) Module.

(Continued on page 2)
These separate processes communicate with each other as well as share common data files that contain information about the target description and threat, as well as output from an analysis. The AJEM User Interface aids the analyst in managing the various input files required for an assessment, controls the operation of the Encounter and Vulnerability/Lethality Modules, and provides access to a number of tools that support an analysis. Some of these tools include an Encounter Visualization Tool (shown in Figure 1);

![Figure 1. AJEM Encounter Visualization Tool](image1)

the BRL-CAD™ modeling and visualization tool MGED, developed and maintained by the Army Research Laboratory (shown in Figure 2);

![Figure 2. MGED released with BRL-CAD](image2)

intermediate and final results postprocessors and viewers (final results viewer shown in Figure 3), and detailed documentation and references on-line in HTML format. Both the AJEM and MGED interfaces are Tool Command Language and Toolkit (Tcl/ Tk) based windowing programs rather than hardware dependent graphic routines. This allows the user to reconfigure the windows to suit individual preferences by creating and using Tcl/ Tk scripts; it also provides access to all of the BRL-CAD tools.

![Figure 3. AJEM Final Results Viewer](image3)

A major advantage to the AJEM user is that all endgame and target-interaction calculations work with the same BRL-CAD™ geometry. A number of commercial geometry formats can be imported into the BRL-CAD data base. Further, the recent release of BRL-CAD 5.4 includes complete FASTGEN primitive support. BRL-CAD 6.0 will be released by ARL in October, 2001 and will provide a significant increase in capability. The data base has been changed to allow arbitrary text attributes to be assigned to objects. Additionally, the databases will be able to contain other arbitrary information, such as MUVES inputs, Pro/E geometry, texture maps, etc. BRL-CAD 6.0 will be included in AJEM V2.0.

The Encounter Module is a separate program that models the terminal engagement of a missile with a target. It has the ability to use various fuze models and interacts with the BRL-CAD target description to predict warhead burst points or missile impact locations on a target. Once the burst points are determined, the Encounter Module provides the option to run the Vulnerability/Lethality Module to determine target Pk. The Encounter Visualization Tool (EVT) can read the input and output of the Encounter Module and animate the encounter to assist the analyst in visualizing the results of a run (as shown in Figure 1).

(Continued on page 3)
At the heart of AJEM is the Vulnerability/Lethality (V/L) Module. It provides all of the vulnerability analysis capabilities for API and HEI projectiles, warhead fragments and blast, missile body hits, long rods, shaped charges, EFPs, and behind-armor-debris. AJEM uses the U.S. Army Research Laboratory Modular Unix-based Vulnerability Estimation Suite (MUVES) as the V/L Module. MUVES provides the capability to add new physics-based target interaction models as linked libraries. One of these is the FATEPEN penetration and damage model, which allows the realistic analysis of fragments, projectiles, and long rods. This model includes penetrator path deflection and the tracing of fragment debris particles. A comparison of traditional- and FATEPEN-predicted fragment damage with test results is shown in Figure 4. Capabilities are being added to FATEPEN to predict penetration and fuzing of Man Portable Air Defense Systems (MANPADS).

AJEM can provide more realistic predictions primarily because it traces the actual threat path through a target and calculates the vulnerability/lethality on the fly rather than use precalculated vulnerability data and interpolated results. It can be used for evaluating a single threat against a single target or multiple threats versus single or multiple targets. In the case of multiple threats, damage data is realistically accumulated and the results are assessed at the end; current models incorrectly assume an undamaged target with each additional threat. In addition AJEM has new target interaction capabilities that are not available in other models, and these are continuing to be improved. Other target interaction models are being developed, such as fire start and sustainment, and will be integrated into AJEM in the near future.

Distribution of the AJEM software is limited to US Government Agencies and their contractors. For more information, visit the AJEM website at www.ajem.com. Any questions regarding AJEM can be addressed to Mr. Thomas Wasmund, the AJEM Model Manager, at (540) 653-8692, Dr. Paul Tanenbaum, the MUVES Model Manager, at (410) 278-6649, or Ms. Lisa Garriques at the SURVIAC Aberdeen Satellite Office, (410) 273-7722.

About the Author: Mr. Wasmund received his B.S. in Electrical Engineering from the University of Washington, and B.S. and M.S. degrees in Aerospace Engineering from the Naval Postgraduate School. He is a Senior Scientist in the Lethality and Weapons Effectiveness Branch of the Missile Systems Division, Naval Surface Warfare Center, Dahlgren Division. He has 30 years experience in air target vulnerability analysis, testing, and technology development, primarily working with foreign air targets and supporting missile warhead development. Mr. Wasmund is the Functional Area Coordinator for Air Targets for the Vulnerability Working Group of JTCG/ME, a co-chair of the Vulnerability Committee of the JTCG/AS Survivability Assessment Subgroup, and the AJEM Model Manager. He may be reached at wasmundTL@nswc.navy.mil.
Anti-Jam GPS Part 1
GPS Employment In PGMs

by Mark Scott
IIT Research Institute

Background

When recently shopping in an office supply store, I happened upon an electronic device for sale for around $100. The device had the size and appearance of a cell phone. Upon closer examination, I realized I was holding a personal Global Positioning System (GPS) receiver. These navigation devices have shrunk in size, weight, and cost in recent years to become a garden variety commercial product.

Such was not always the case. In 1977, on my first job out of college for the Instrument Division of Lear Siegler (now part of Smiths Industries), the hardware for our in-house prototype GPS receiver testbed occupied a rack 2 feet wide x 3 feet deep x 5 feet tall. GPS was originally envisioned by the U.S. Air Force as a world-wide, instantaneous navigation system with the accuracy and long-term stability required for aircraft missions; accordingly, early receiver specifications did not exhibit severe size/weight constraints. The dramatic miniaturization and cost reduction in GPS receivers, made possible by continuing advances in electronics technology, have opened a plethora of applications for GPS navigation, both commercial and military—well beyond the expectations of the system’s designers.

Among the expanding military roles of GPS is its employment as a navigation subsystem in Precision Guided Munition (PGM) applications. In these applications, a GPS receiver, usually coupled with an inertial navigation system (INS), is built into an indirect fire munition. The coupled GPS/INS navigator gives the munition the capability to precisely (within about 10 meters) determine its position in space and time, in a real earth coordinate system. An onboard processor can then compare the weapon’s actual position to its planned trajectory (that leads to specified target coordinates) and generate guidance corrections to null out the calculated errors. The specified “fly to” point can be the actual coordinates of the target; a target acquisition basket for an onboard seeker; or a dispense point for smart submunitions.

For the case of flying to the actual target coordinates, the PGM is referred to as a “competent” munition - the PGM is competent to hit specified, fixed target coordinates, but does not have the “smarts” to address significant target location errors or a target that moves after the weapon has been launched.

A sample of U.S. weapons that currently employ or are planning to incorporate onboard GPS receivers include the following PGMs by service: Navy: ERGM, Tomahawk, HARM, Harpoon, SLAM & SLAM-ER. Air Force: EGBU-15, P-LO CAAS. Army: Excalibur, Hornet, PG M M, G M LRS, ATACMS. Joint Service: JSO W , JDAM & JDAM-ER, JASSM. With this proliferating utilization of GPS in U.S. weapons, concerns have risen over our growing dependence on GPS for precision guidance and over the potential vulnerability of GPS receivers to jamming—especially in weapon applications.

This article marks the first in a two-part series addressing anti-jam (AJ) GPS technology as it applies to PGM systems facing potential threat jamming environments. This article will describe the fundamental features of GPS navigation for PGM applications. The subsequent article will describe the essential features of GPS signal reception, the potential GPS jamming threat, and the main thrusts in counter-countermeasures that are being pursued to realize an AJ GPS capability in current and future PGM systems.

GPS Navigation Fundamentals

GPS navigation is based on measuring ranges to satellites in six precisely specified orbits. There are four satellites in each orbit for a total of 24 satellites in the GPS constellation. The orbits are at a relatively high altitude of 20,190 km, corresponding to an orbital radius of 26,560 km (see Figure 1).

![Figure 1. GPS Satellite Orbit](image)
The radius and orientation of the orbits are designed such that four or more (and usually at least six) satellites are always in view from anywhere on earth.

The GPS satellites transmit radio frequency (RF) microwave signals in L-band around 1.5 GHz. These signals are modulated with data and pseudo-random binary codes to enable measurement of the signal’s propagation time from the satellite to the weapon’s receiver. This measurement is accomplished by comparing the binary code sequence received from the satellite with a local replica of the code generated at the receiver (see Figure 2). The delay in the received code relative to the local code represents the signal propagation time.

Since all electromagnetic radiation travels at the speed of light \( c \approx 3 \times 10^8 \text{ m/sec} \), the GPS signal propagation time \( \Delta t_p \) can be directly translated into the range \( R_s \) between the satellite and the receiver: \( R_s = c \Delta t_p \). The receiver also knows precisely where the satellite was when it transmitted the signal, based on ephemeris data encoded on the signal. With both satellite position and range data, the receiver now knows that it resides somewhere on a sphere of radius \( R_s \), centered on the satellite.

Ranging on another satellite determines another sphere of possible positions. The intersection of these two spheres defines a circle of possible receiver positions. The sphere around a third satellite will intersect this circle in two points (see Figure 3). These two points are both possible positions for the GPS receiver. Typically, one of these represents a physically unreasonable result (often outside the satellites’ orbits), and hence can be rejected, leaving a unique navigation solution (again, see Figure 3). Hence, acquisition of ranging signals from three satellites is theoretically sufficient to precisely determine a receiver’s position.

The set of equations that must be solved in the processor of a weapon’s GPS receiver to give the navigation solution are:

\[
R_s^2 = (x_w - x_i)^2 + (y_w - y_i)^2 + (z_w - z_i)^2
\]

for \( i = 1, 2, 3 \)

where

\[
R_s = \text{range from weapon to satellite \#i} \\
(x_i, y_i, z_i) = \text{position vector of satellite \#i} \\
(x_w, y_w, z_w) = \text{position vector of weapon}
\]

The position components, \((x, y, z)\), are in an earth-centered inertial (ECI) cartesian coordinate frame. The satellite position vectors are known. The ranges to the satellites are measured by the receiver. The components of the weapon’s position vector are to be solved for.
This system of simultaneous quadratic equations represents the algebraic equivalent to the geometric navigation solution illustrated in Figure 3. Solving the system will yield two solutions (p & q), the valid solution being the one that is in closer proximity to the earth’s surface; viz., \( p=(x_w, y_w, z_w) \).

One practical obstacle must still be surmounted before the above proposed navigation solution will yield accurate results. The ranges to the satellites are computed based on the propagation times of the GPS signals traveling from satellites to receiver. The signal propagation time is identically the delay in the received satellite signal compared to the replica signal generated locally in the receiver. A clock error at either the satellite or the receiver causes a shift in the relative phase between received and local signals, and leads to an erroneous measurement of time delay in the received signal: 1 microsecond of error \( \times (3 \times 10^8 \text{ m/sec}) = 300 \text{ meters of range error.} \)

The satellites carry redundant atomic clocks, employing cesium and rubidium frequency standards. Not only are these clocks very accurate (a few nanoseconds), but they are also monitored and corrected from the ground control station on a daily basis. Obviously, very few GPS users could afford a similar time standard for their receivers. The crystal time standards that are practical for employment in receivers will inevitably introduce a bias error into the time delay measurements. This timing error will translate into a bias error in each of the satellite range calculations.

Fortunately, there is a relatively easy way around this problem. Since the clock bias is at the receiver end, the resulting bias error \( (\delta) \) is the same for the range measurement to each satellite. The first step toward eliminating this error is to acknowledge it as an additional unknown in the navigation solution:

\[
(R_i + \delta)^2 = (x_w - x_i)^2 + (y_w - y_i)^2 + (z_w - z_i)^2
\]

\[
\text{for } i = 1, 2, 3
\]

Now there are three quadratic equations in four unknowns; viz., the three unknown weapon position coordinates, \((x_w, y_w, z_w)\), and the unknown range bias error, \( \delta \). The way to obtain a fourth equation to solve this system is to acquire and range on a fourth satellite (the bias error will be the same for this fourth range measurement as it was for the first three, since it has a common source resident in the receiver’s clock):

\[
(R_i + \delta)^2 = (x_w - x_i)^2 + (y_w - y_i)^2 + (z_w - z_i)^2
\]

\[
\text{for } i = 1, 2, 3, 4
\]

Thus, while only three satellite range measurements are necessary for a receiver with perfect timing, a fourth measurement is a practical means of compensating for the bias error associated with an affordable receiver clock.

**Summary**

This concludes the introduction to GPS navigation principles. The basis for obtaining a position fix with GPS is the receiver’s acquisition of the signals transmitted from the satellite constellation. It is the acquisition and tracking of these signals that permits a receiver to range on the known positions of the GPS satellites. In a subsequent bulletin, Part 2 of this article will address the characteristics of the GPS signals, reception of these signals, the potential jamming threats, and the anti-jam features that are emerging specifically to address applications of GPS aimed at precision guided weapons.

**About the Author**

Mark Scott received B.S. and M.S. degrees in Electrical Engineering from Michigan State University in 1974 and 1976 respectively. From 1977 to 1982 he was employed by the Instrument Division of Lear Siegler, Inc., working on tactical avionics systems. From 1982 to 1984 he was employed by IIT Research Institute, performing countermeasure/counter-countermeasure (CM/CCM) analyses on air defense radars. From 1984 to 1987 he was with Harris Corporation working on airborne data links, after which he rejoined IITRI. His current research interests include sensor/countermeasure performance analysis, signal processing, and sensor fusion for smart weapons, multisensor seekers, survivability suites, and C3I applications. Mr. Scott is a member of IEEE, the IEEE Aerospace and Electronic Systems Society, and the Association of Old Crows.

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The world has changed. The events that up to now we only saw on TV broadcast from other countries were brought much closer to home on 11 September 2001. The devastation and loss of life that occurred in New York, Washington, DC, and Pennsylvania will necessarily lead to major changes in our Nation’s approach to internal security and homeland defense. Hopefully, the United States and the rest of the world will become a safer place to live as a result of the actions that will now be taken to eliminate terrorists throughout the world. We now need to consider how we can dedicate our personal efforts to help ensure that this won’t happen again. For those of you directly affected by this tragedy, my family and I offer our thoughts and prayers to you, your families and friends.

This issue of the WSTIAC Newsletter features an article by Mr. Tom Wasmund, Naval Surface Warfare Center – Dahlgren Division, that discusses the Advanced Joint Effectiveness Model (AJEM). AJEM is a new DoD model that can be used to make realistic estimates of weapons effects against aircraft, missiles and ground-mobile targets. This model leverages many years of effort by all three Services and the Joint Technical Coordinating Groups and incorporates and improves on the capabilities of a number of older models. AJEM is available to DoD Users through SURVIAC; see the www.ajem.com web site for information on model availability.

This issue of the WSTIAC Newsletter also features a technical article on the Global Positioning System (GPS), contributed by Mr. Mark Scott, a Senior Science Advisor at the IIT Research Institute. This is the first of a multi-part series that will discuss Anti-Jam GPS technology. Such technology is being incorporated in GPS receivers on-board precision-guided munitions to project them against jamming.

We welcome your feedback about the WSTIAC Newsletter and solicit your suggestions for future topics you would like to see included. You can reach me by Email at wkitchens@iitri.org or by phone at (703) 933-3317.

Secretary of Defense Donald Rumsfeld’s Comments on CLASSIFIED INFORMATION

“And it seems to me that it’s important to underline that when people deal with intelligence information and make it available to people who are not cleared for that classified information, the effect is to reduce the chances that the United States government has to track down and deal with the people who have perpetrated the attacks on the United States and killed so many Americans. Second, when classified information dealing with operations is provided to people who are not cleared for that classified information, the inevitable effect is that the lives of men and women in uniform are put at risk.”
Publications from the National Academy of Sciences

REVIEW AND EVALUATION OF THE AIR FORCE HYPersonic TECHNOLOGY PROGRAM
This study was undertaken in response to a request by the U.S. Air Force that the National Research Council (NRC) examine whether the technologies that underlie the concept of a hypersonic, air-launched, air-breathing, hydrocarbon-fueled missile with speeds up to Mach 81 can be demonstrated in time to be initially operational by 2015. To conduct the study, the NRC appointed the Committee on Review and Evaluation of the Air Force Hypersonic Technology Program, under the auspices of the Air Force Science and Technology Board.
Availability http://www.nap.edu/catalog/6195.html

NAVAL MINE WARFARE: OPERATIONAL AND TECHNICAL CHALLENGES FOR NAVAL FORCES (2001)
The Naval Studies Board conducted a mine warfare assessment that examined issues related to both countermine and future sea mining capabilities. The committee evaluated present and future threats to deep sea and littoral operations involving mines; reviewed current R&D programs aimed at providing the fleet with improved capabilities; and studied the status of present sea mine stockpile and mine delivery systems with specific emphasis on that part of the littoral region that extends from a sea depth of 40 ft. to 200 ft. across the beach.
Availability: http://www.nap.edu/catalog/10176.html

NAVAL FORCES' CAPABILITY FOR THEATER MISSILE DEFENSE
The Navy and Marine Corps have acknowledged a shift in warfare from operations on the open seas to operations in and adjacent to littoral areas. This shift in warfare location presents many technical and operational challenges to naval forces in power projection, the most notable of which may be an increase in the land-based threat to the forces engaged in such operations. Both theater ballistic missile defense and cruise missile defense including anti-ship cruise missile defense and over land cruise missile defense are important emerging military capabilities that are inherently necessary if naval forces are to execute missions in littoral areas.
Availability: http://www.nap.edu/catalog/10105.html

ALTERNATIVE TECHNOLOGIES TO REPLACE ANTIPERSONNEL LANDMINES
The Committee on Alternative Technologies to Replace Antipersonnel Landmines was asked to identify and examine possible tactics, technologies and operational concepts that could provide advantages similar to APL; suggest a near-term alternative technology, weapon or combination of systems and describe how these technologies could be used consistently with current tactical doctrine. This report is the result of that study.
Availability: http://www.nap.edu/catalog/10071.html

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JDAM Marries Up with Super Hornet

PEO Strike Weapons and Unmanned Aviation

Naval Air Systems Command
Public Affairs Department

The first guided launch of a Joint Direct Attack Munition (JDAM) from an F/A-18E Super Hornet scored a direct hit to its target Aug. 29 at the Naval Air Systems Command Weapons Division China Lake, Calif., test range.

Released from the F/A-18E flying at 550 knots at 7000 feet, the JDAM demonstrated the effectiveness of mating its guidance kit to a BLU-109 warhead — a 2000-pound hard target penetrator. The weapon slammed home, knocking out the Howitzer target.

Super Hornet pilot was Cdr. Ed Gassie from the NAVAIR Weapons Division Weapons Test Squadron located at China Lake.

Lt. Cdr. Don Simmons, JDAM Chief Systems Engineer, applauded the weapon's effectiveness stating, "This is another weapon that fully exploits the capabilities of the Super Hornet giving it unparalleled lethality in adverse weather."

The JDAM has been used successfully by the U.S. Navy and Air Force during combat operations.

Hypersonic Scramjet Projectile Flies

Defense Advanced Research Projects Agency
Office of Public Affairs

The Defense Advanced Research Projects Agency (DARPA) announced today the first-ever successful free flight of a hypersonic projectile powered by a supersonic combustion ramjet (scramjet) engine burning hydrocarbon fuel. The projectile is a four-inch diameter, 20-percent scale model of a conceptual missile. On July 26, GASL Inc., of Ronkonkoma, N.Y., fired the scramjet projectile out of a large gun at the Air Force's Arnold Engineering Development Center, Arnold AFB, Tenn. The test is an important step towards the realization of flight at hypersonic speeds.

Scramjet engines provide propulsion at speeds above Mach 5 by capturing atmospheric air to burn on-board fuel. These air-breathing engines are more efficient than rocket motors for hypersonic propulsion, and will ultimately allow the possibility of longer duration flight with greater payload. Applications for such engines include powering long-range hypersonic missiles, gun-launched kinetic energy weapons, and access to space vehicles. In order to operate, scramjet engines must first be traveling at hypersonic speed. An accepted approach to reach scramjet takeover speeds is to attach the scramjet to a rocket booster as a first stage and then operate the scramjet once the rocket has increased the speed sufficiently.

MLRS and Army TACMS/Bat Merge

By Skip Vaughn

Precision Fires. That's the new short name for what used to be two separate project offices: MLRS and Army TACMS/Bat. The Precision Fires Rocket and Missile Systems Project Office was formed Aug. 6 from the merger of the Multiple Launch Rocket System and Army Tactical Missile Systems/ Bat offices.

This project that stands up today is going to have dramatic impact on the future of our Army,” Brig. Gen. John Holly, the program executive officer for tactical missiles, said during the deactivation/activation ceremony that morning in Bob Jones Auditorium.

Col. Craig Naudain, the former MLRS project manager, assumed the reins for Precision Fires. "We are and will be the center for excellence in the world in production and development, sustainment and fielding of these weapon systems,” Naudain said.

Col. Kelley Griswold, the former Army TACMS/Bat project manager, will become director of information technology and special programs for the Program Executive Office for Tactical Missiles. "I'm extremely proud to have been a part of the Army TACMS/Bat team,” Griswold said.

Reprinted from the Redstone Rocket, — 15-Aug-2001
is pleased to announce the 2002 schedule for its

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The Weapon Systems Technology Information Analysis Center (WSTIAC) developed this 2-1/2 day Smart Weapons Training Seminar to provide a comprehensive understanding of smart weapons and related technologies. This seminar is aimed at providing general knowledge about smart weapons technology and a source of current information on selected U.S. and foreign smart weapons, to include system description, concept of employment, performance status.

Objective:
The seminar’s objective is to inform materiel and combat developers, systems analysts, scientists, engineers, managers and business developers about smart weapons, to include:

- State of the art of representative U.S. and foreign smart weapons systems;
- Employment concepts;
- Smart weapons related systems, subsystems, and technologies; and
- Technology trends.

Seminar Sponsors:
- DUSD (S&T) Weapons Systems Directorate
- Defense Technical Information Center (DTIC)

About the Seminar:
This seminar was originally developed for the U.S. Army Command and General Staff College, Fort Leavenworth, Kansas. It has proven to be enormously popular with attendees from both government and industry. The seminar is updated annually to include current information about the latest technology and capability upgrades being made to representative U.S. and foreign smart weapon systems.

For a complete brochure for the Huntsville course and/or on-site course information, contact Mrs. Shirley Hardy, Seminar Administrator, at (256) 382-4756 or by e-mail: shardy@iitri.org
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http://register.ndia.org/interview/register.ndia?~Brochure~234

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http://www.mein.nagoya-u.ac.jp/IEEE-NANO/

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For additional information:
http://www.icra-iros.com/iros2001/

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http://register.ndia.org/interview/register.ndia?~Brochure~252

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