Precision Maritime Inshore Navigation with a Tightly-Coupled Sensor System

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BIOGRAPHY

Alison Brown is the President and Chief Executive Officer of NAVSYS Corporation. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge University. In 1986, she founded NAVSYS Corporation. Currently, she is a member of the Air Force C2ISR Center Advisory Group, the Interagency GPS Executive Board Independent Advisory Team (IGEB IAT), and an Editor of GPS World Magazine. She is an ION Fellow and was inducted into the SBA "Wall-of-Fame" in 2003.

David Boid is a Senior Software Engineer at NAVSYS Corporation, where he is responsible for GUI and database software development in various GPS/INS/video integration applications. Previously, he was employed as a Senior Developer by IBM Corporation, where he was lead architect responsible for development of multiple systems including the NASA Space Shuttle telemetry data management system and NORAD Cheyenne Mountain security augmentations for B2-level security. He has a BS in Computing Science from Texas A&M University."

ABSTRACT

This paper describes an integrated sensor system for precision maritime surface navigation in tightly confined harbor environments. The system tightly integrates GPS, inertial, image and laser measurements with an onboard electronic charting system to provide accurate bearing and/or range measurements to known navigational aids, allowing robust and accurate piloting relative to navigation aids and hazards. The system provides the ability to input automatic visual fixes into an ECDIS-N electronic charting system with little operator involvement.

The system architecture is described, navigation integration and automatic calibration techniques are derived, and results reported. In the summer of 2002, two of the systems, integrated with an onboard electronic charting system, were tested at sea near Annapolis, MD. The results of the trials showed the ability of the system to improve the accuracy by a factor of 10 over current visual fix methods. At the same time, the system improves the frequency and timeliness of visual fixes while reducing crew workload when compared with current piloting techniques.

INTRODUCTION

More than ever, U.S. Navy ships require accurate and timely information about their exact position both in the open ocean and during piloting operations when maneuvering is restricted. Various iterations of Global Positioning Systems (GPS) have resulted in increased accuracy when used for a variety of targeting systems and provide a ship's exact position on the earth, yet multi-billion dollar ships experience the same level of risk when piloting in shallow waters and channels as they did since the days of sail. Although modern day electronics, from radar to GPS and INS, have added to the navigator and captain's ability to be more aware of their ship's position, the safe navigation of the ship requires that they know their exact location based on visual references.

Today, as depicted in Figure 1, sailors are required to determine a ship's bearing by manually sighting at least two visual references using a telescopic alidade located at gyrocompass repeater stations. A "bearing-taker" sights a navigational aid (NavAid) through the alidade and relays the true bearing of that aid at a prescribed time "mark" to the navigator on the bridge via sound-powered phone or other remote communication device. A "bearing-recorder" manually writes the true bearing of each NavAid in a logbook, whereupon the a Quartermaster or the navigator plots the lines of bearing (LOBs) at the time of the sightings, determines where the LOBs intersect, and then advances the LOBs so as to estimate the exact location of the ship from "where it was" at the time of the sightings. This is a manually intensive and, therefore, possibly error prone task that must be performed quickly to ensure the vessel's course can be charted accurately. It is estimated that this process, from time of "mark" to the time the Captain of the ship is told where he is in relation to his ship's Plan of Intended Movement (PIM), takes at least one full minute—a ship making 6 knots will travel approximately 225 yards (206 meters) in that amount of time, which is 1.2 times the length of an *Arliegh Burke*-class guided missile destroyer, built at a cost of $1.1 billion.

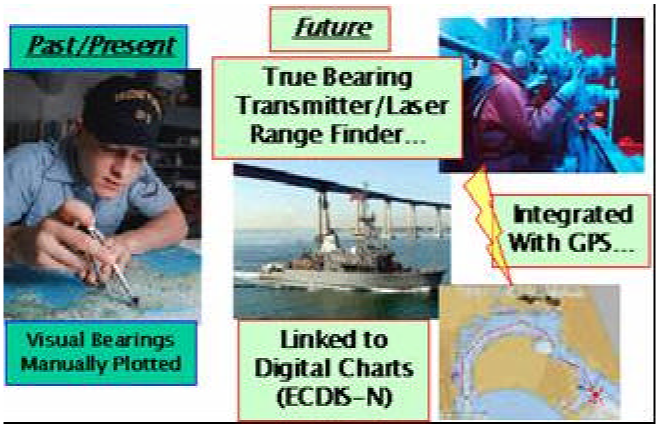

Figure 1 Maritime Piloting: Past, Present, and Future

U.S. regulations have recently been changed to authorize naval vessels to use electronic navigation (33CFR 164.01). Electronic navigation is typically supported solely by GPS, which is subject to any inaccuracies in datum transformation whereas relative (visual) navigation eliminates this problem. Also, loss of GPS signal is a risk that could be obviated through integration of visual navigation with electronic chart systems. Thus, there is an emerging need for an innovative system to capture and display visual lines of bearing to provide navigators with a capability for relative navigation with electronic charts rather than having to revert to paper chart navigation. To improve maritime safety, it is imperative that real-time information be displayed to aid navigation as ships are maneuvered within the ports of the world. The ECDIS-N Performance Standard includes integration of visual navigation as a capability of ECDIS-N.

The Maritime Piloting and Marine Feature Collection (MP/MFC) prototype, shown in Figure 2, has been developed to demonstrate such capability. This integrated device consists of a true bearing instrument, a laser rangefinder, and a digital camera, which can be used to feed the ECDIS-N aboard Navy vessels to plot the ship's current position on a digital nautical chart (DNC) in real-time for the navigation team. Furthermore, these digital images could also be used during piloting operations to positively identify navigational aids (e.g., buoys, daymarks, smokestacks, water towers), their positions, and feed accurate, up-to-date information back to NIMA to maintain the DNC library.

Figure 2 MP/MFC Prototype

TECHNICAL APPROACH

Two MP/MFC prototype devices, one on each bridge wing, measured true bearing and range to fixed objects with an integrated inertial navigation system and laser-aided range finding device and sent that data to ECPINS for plotting an accurate position on DNCs. Figure 3 shows the high-level architecture.

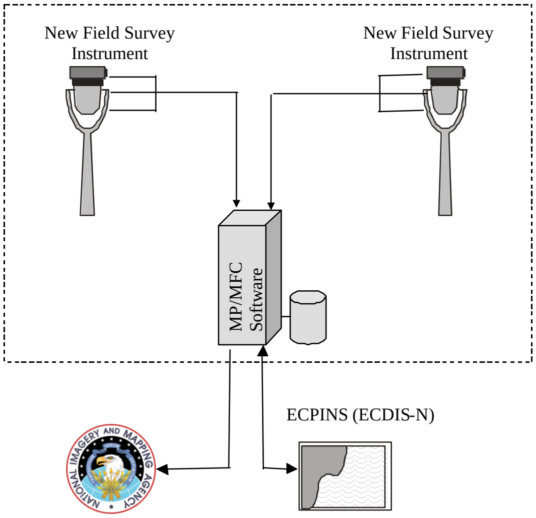

Figure 3 High-Level MP/MFC architecture

The system consists of the following six main parts (three hardware assemblies and three software components):

1. GPS/Inertial Navigation System (GI) –determine true bearing,
2. Laser Rangefinder (LRF) - determine range,

3. Digital Camera – capture image of the navigational aid to be used for accurate NavAid selection and NIMA post processing,
4. Real-Time Software – process sensor outputs and forward data to ECDIS-N,
5. Post-Processing Software – package data for NIMA and determine accurate NavAid location based on true ship's position, and ECPINS – modified ECPINS software that supports the interface to the new MP/MFC prototype system.

REAL-TIME OPERATIONS

The MP/MFC device provides both range and bearing to objects within visual range. Once the vessel was underway, the ship's navigator followed the navigation plan or PIM, calling for visual fixes approximately every two minutes. The real-time operating architecture is shown in Figure 4. Steps 1-4 below describe the steps taken for each set of visual fixes.

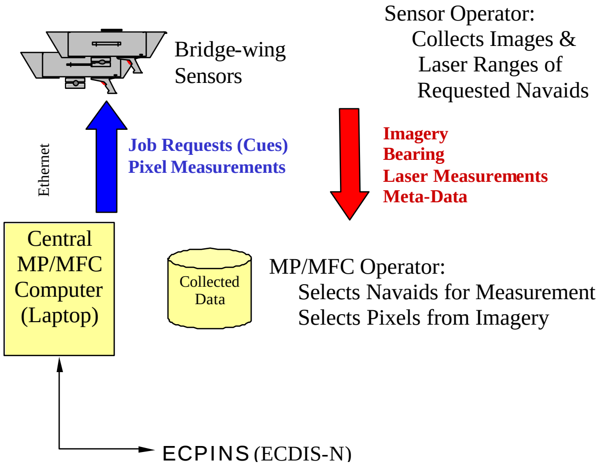

Figure 4 MP/MFC Real-time Operating Architecture

STEP 1: SELECT NAVAID AND CUE SENSOR

The navigator verbally cued the ECPINS and MP/MFC operators when it was time to take a measurement and told them which NavAids to use. The MP/MFC operator then selected from a list the NavAid(s) to be used by each sensor head for this visual fix (see the popup window in the lower left corner of the screen shot shown in Figure 4.) The MP/MFC central computer then sent the collect command with the expected range and bearing to the appropriate sensor for cueing of the sensor operator.

STEP 2: TRIGGER SENSOR AND COLLECT DATA

Upon notification, the sensor operator aligned the crosshairs on his screen with the currently selected NavAid (see Figure 5) and triggered the device on the verbal "Mark" command. The bridge wing sensor captured and time tagged all necessary data and forwarded it to the central MP/MFC computer.

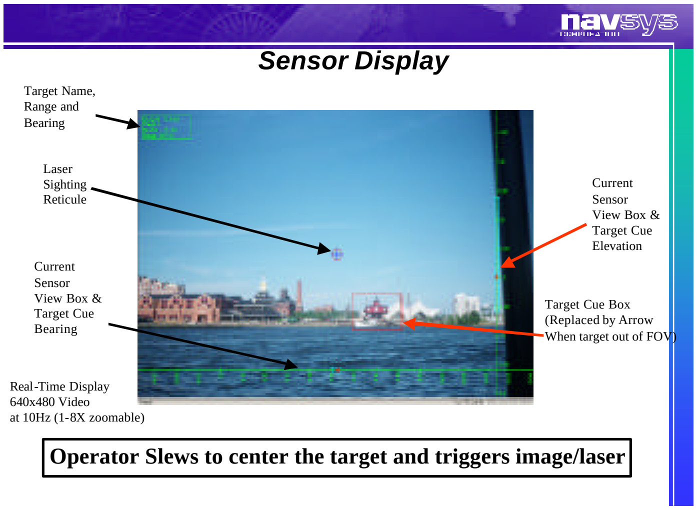

Figure 5 Sensor Display

STEP 3: VERIFY RANGE AND SELECT NAVAID FROM IMAGE

The collected image and associated data was automatically shown on the MP/MFC's display. The MP/MFC operator then compared the measured range with the expected range to determine if the range was valid. The expected range and bearing was displayed in the top right hand portion of the MP/MFC display (see Figure 6), and the measured range and bearing was displayed directly below it. If a range was not collected by the LRF, the measured range displayed 0. If the range was not valid, the box labeled "Accept Range" was left unchecked and the range was not sent to ECPINS. Next, the MP/MFC operator used his mouse to move the crosshairs to select the precise location of the NavAid in the image. The real-time software then calculated the bearing and sent the calculated bearing and associated range (if available and correct) to ECPINS for processing and display.

STEP 4: ECPINS

When the "Mark" command was given, the ECPINS operator hit the "Man Overboard" button to place a symbol on the ECPINS display which showed where the vessel was when the first measurements were taken (displayed as the rectangle marked MOB in Figure 7.) When ECPINS received input from the MP/MFC system, a visual fix input screen was automatically displayed and filled in as input was received (see Figure 7). As each measurement was received, previously received values were advanced or "moved forward in time" based on the time difference between the current and previous measurement and the ship's speed. The ECPINS operator also double checked the incoming data for obvious problems and, if necessary, deleted erroneous measurements. Once all measurements were received, the ECPINS operator then hit the “OK” button to complete the data input. Using the lines of bearing and range circle(s) shown on the ECPINS DNC display, the ECPINS operator then selected the most probable location of the ship at the time of the visual fix, establishing an “Estimated Position (EP)” of the ship based on this fix, GPS, and dead reckoning (DR) track. (Note: ECPINS could easily automate this step and determine the most likely location of the ship. However, navigators have resisted this step and choose to manually select the ship’s location.)

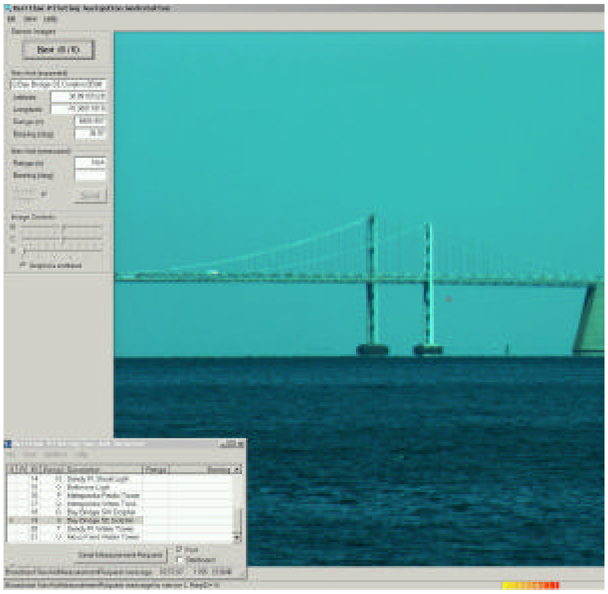
Figure 6 MP/MFC Operator Screen Shot


Figure 7 ECPINS Display

POST-PROCESSING OPERATIONS

The post-processing architecture, shown in Figure 8, consists of post processing the collected data for GPS corrections, packaging the data, and transporting it to NIMA’s DNC office. This step is completed after the vessel returns to port.

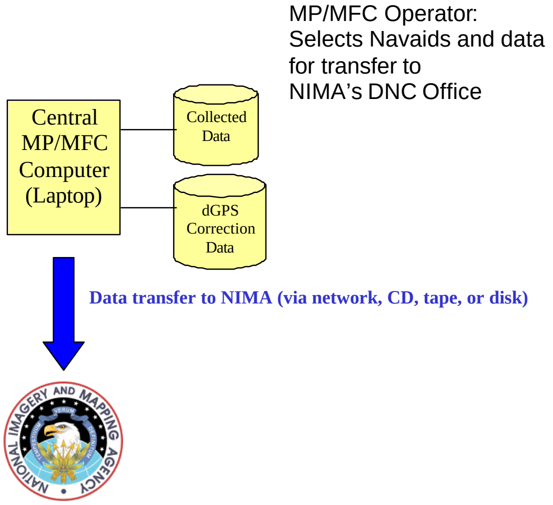

Figure 8 MP/MFC System Post-processing Architecture

TEST AND DEMONSTRATION

The Office of Naval Research (ONR) Yard Patrol Craft (YP-679) research vessel based at the U.S. Naval Station in Annapolis, Maryland, was used to support testing and demonstrations (see Figure 9). The ONR YP, operated and maintained under ONR contract by Anteon Corporation, included a crew of four, one of whom was responsible for navigation. YP 679 is 108 feet long, 22 feet 9 inches wide, and has a maximum speed of 13 knots.

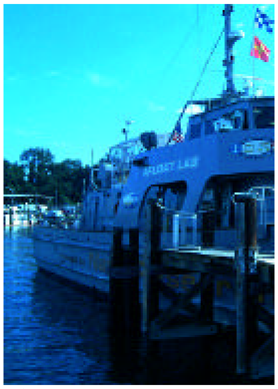
Figure 9 ONR YP

The MP/MFC central computer and ECPINS system were located side-by-side on the bridge of the YP. A MP/MFC sensor head was placed on each of the port and starboard bridge wings. Cabling was run down through the pelorus stand to the vessel’s Ethernet network and power supply for safety and ease of installation.

During normal Navy operations, the ship’s navigator, ECDIS-N operator, and MP/MFC operator could be a single person. However, for this test, two operators were used for the ECDIS-N and MP/MFC systems respectively. To simulate actual navigation procedures, an experienced active duty senior enlisted person with extensive experience acted as the navigator.

Because it was desirable to have as many different marine conditions as possible over the three-day testing period, afloat tests were scheduled for both the morning and afternoon. During the first day of testing, winds of up to 33 knots were encountered. This caused enough chop in the water to affect the MP/MFC sensor operator's ability to center on the navigation aid. However, because the exact location of the NavAid was selected by the MP/MFC operator from the image taken, the test demonstrated it was possible to maintain the system's accuracy in adverse weather conditions.

The test and demonstration phase was conducted 9-13 Sep 2002. The first day was devoted to equipment installation and NavAid surveys. Day two included at-sea tests without outside observers. Tests and demonstrations were held twice daily at 8 a.m. and 1p.m. for approximately two hours each on 11 and 12 Sep 2002.

The following functions were tested (test items follow in parentheses):

- Bearing (Navigation System, Camera, Real-time Software)
- Range (Laser Rangefinder)
- NavAid data transfer from ECPINS to MP/MFC system (ECPINS and Real-Time Software)
- Real-time range and bearing data feed from MP/MFC system to ECPINS (Real-Time Software and ECPINS)
- Packaged data for NIMA (Post-Processing Software)

TEST APPROACH

The MP/MFC system, both the real-time operating architecture shown in Figure 4 and the post-processing architecture shown in Figure 8, was tested in four phases:

1. Aboard Vessel
2. Data Gathering
3. Underway
4. Post Processing

ABOARD VESSEL

ECPINS was used by the ship's navigator and NCAT prototype team to build a navigation plan. When complete, the NavAids included in the navigation plan along with their data (ID, location, and description) was sent to the MP/MFC system for ingestion. For the testing, the National Oceanic & Atmospheric Administration (NOAA) and the US Coast Guard (USCG) provided the team with a list of updated survey points that could be used. The surveyed location was recorded and compared with the NavAid's DNC location in the DNC library for accuracy. This test data is summarized in Table 1. Post-test, the logged data from the ship and reference station was re-processed using DGPS corrections to determine true ships position to within approximately 1.5 meters. This truth data was then used to validate the bearing and range measurement accuracy of the system.

UNDERWAY

The navigation plan included use of at least six fixed aids to navigation, several of which were daymarks, and one floating aid to navigation. Navigation fixes were evaluated:

- Using only fixed aids and landmarks:
  - Use bearings only with interaction with MP/MFC operator,
  - Use bearings and ranges with interaction with MP/MFC operator,
  - Use bearings only without interaction with MP/MFC operator,
  - Use bearings and ranges without interaction with MP/MFC operator,
- Using a fixed daymark:
  - Use bearings only with interaction with MP/MFC operator,
  - Use bearings and ranges with interaction with MP/MFC operator,
- Using a floating aid:
  - Use bearings only with interaction with MP/MFC operator,
  - Use bearings and ranges with interaction with MP/MFC operator.

Table 1 DNC - GPS Location Comparison

Id	Description		GPS	DNC	Diff(m)	GPS	MP/MFC	Diff(m)
B	Chapel Dome	Lat	38.981561	38.981564	0.33	38.981561	38.98151	5.6
		Long	-76.486384	-76.486381	0.26	-76.486384	-76.486363	1.8
D	Capital Dome	Lat	38.978761	38.978741	2.22	38.978761	38.978721	2.2
		Long	-76.490888	-76.490829	5.11	-76.490888	-76.490804	2.2
F	Greenbury Pt Light	Lat	38.968236	38.968208	3.11	38.968236	38.9682	3.9
		Long	-76.454167	-76.454196	2.51	-76.454167	-76.45411	4.9

POST PROCESSING

After visual navigation was complete, the collected data was post-processed. While the vessel was underway, a Differential GPS (DGPS) receiver mounted to the mast collected and recorded the ship's location. This data, along with DGPS corrections downloaded from a GPS ground station located in Annapolis, Maryland, was used to increase the accuracy of the ship's position. This is necessary to support using the data collected as survey data. The data was packaged and written to a CD for NIMA's DNC Office. The same software was used to determine the location of each NavAid in the navigation plan. This location was compared with the surveyed the DNC stated location. As shown in Table 1, the comparison of GPS to DNC and GPS to MP/MFC results show only minor differences within the expected accuracy of the system.

TEST RESULTS

The field test successfully demonstrated one prototyped system consisting of two identical sensors that captured three (3) or more visual lines-of-bearings and two (2) laser-measured ranges and presented those readings as a ship's position on a digital nautical chart (DNC) in real-time.

The following requirements were tested:

- Bearing accuracy: 0.10°
- Bearing precision: 0.05°
- Laser Rangefinder accuracy: 5 meters at 100m to 2,866m
- Image resolution: at least 1280 x 1024 pixels

BEARING ACCURACY

To assess the accuracy of the sensor attitude, the difference between the measured and true bearing to the target is used. The error in this value is also a function of the error in the sensor position and the surveyed NavAid position. However, if the range to the target is large, the dominant component in this difference becomes the attitude error of the sensor. A target with a number of images at long range and a GPS surveyed coordinate (the Greenbury Point Radio Tower) was selected. All imagery from one of the missions with range greater than 4000 meters was selected, resulting in 13 samples. Figure 10 shows an example image at 4700 meters. The predicted and measured bearings are shown in Table 2. Mean error is 0.03 degrees with a standard deviation of 0.0802 degrees, which surpasses the 0.1 degree bearing accuracy requirement.

Figure 10 Image of Greenbury Point Radio Tower at 4700 meters

Table 2 Bearing Accuracy Test Results (Greenbury Point Radio Tower)

Range (m)	Predicted Bearing(deg)	Measured Bearing(deg)
4259	328.33	328.45
4712	323.34	323.38
4740	318.52	318.57
4799	311.49	311.55
4748	304.7	304.71
4618	297.61	297.54
4798	290.57	290.46
4958	280.45	280.35
5234	273.85	273.81
5396	270.82	270.8
5570	267.95	267.87
5888	262.43	262.31
6012	259.54	259.41

VISUAL FIX ACCURACY

The overall accuracy of the system is determined by the width of the fix circle (i.e. the distance between where the LOBs intersect). The initial diameter ranged from 2-30 meters (YP length was 22 meters) but improved significantly, down to 2-7 meters, with practice and calmer seas. It was easy to see this distance on the ECPINS display because it was possible to zoom in. However, when using a paper chart to manually plot LOBs, the width of the pencil line can sometimes be up to 10 meters depending on the scale of the map.

SURVEY MODE

Collected survey data was post-processed to account for GPS errors and provided to NIMA on CD-ROM on 17 Sep for analysis by the DNC office. Unfortunately, due to end-of-year commitments, the DNC office was not able to sufficiently analyze the data before the Final Report due date.

CONCLUSION

The test effort successfully demonstrated the use of the Maritime Piloting and Marine Feature Collection (MP/MFC) prototype during sea trial onboard the Office of Naval Research (ONR) Yard Patrol Craft (YP-679) research vessel based at the U.S. Naval Station in Annapolis, Maryland.

The following requirements were tested:

- Bearing accuracy: 0.10°
- Bearing precision: 0.05°
- Laser Rangefinder accuracy: 5 meters at 100m to 2,866m
- Image resolution: at least 1280 x 1024 pixels

While a laser rangefinder was included in the prototype, it was determined that adequate accuracy was supported for piloting operations using image triangulation and this capability may not be required in a final production version of the MP/MFC system.

In addition to its use in determining ship's positions, the MP/MFC system also provides the ship's navigation team a method to determine the relative accuracy of charted data with respect to GPS positioning and ground-truth. This capability will prove most valuable in situations where ships are piloting on charts which they have not used before and in areas where little experience has been gathered by others in the fleet. If chart datum problems exist, they can be detected using this device when the ship is within visual range of charted navigational aids. By a simple comparison of visual position and GPS position track, one can quickly see position inconsistencies. In developing the MP/MFC system, it was determined that the Electronic Chart Precise Integrated Navigation System (ECPINS), developed by Offshore Systems Ltd., would provide the difference in position between primary and secondary tracks.

The demonstration of the MP/MFC prototype successfully showed the capability of current technology to provide real-time viewing of positional data to the navigation team and provide captured data to NIMA to update the DNCs.

ACKNOWLEDGMENTS

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REFERENCES

Maritime Piloting and Marine Feature Collection (MP/MFC) Prototype Final Report dated 30 September 2002, Sponsored By: National Technology Alliance (NTA) and National Center for Applied Technology (NCAT).