



Multiple Image Coordinate Extraction (MICE) Technique for Rapid Targeting of Precision Guided Munitions

Thomas B. Criss, Marilyn M. South, and Larry J. Levy

The effectiveness of weapons guided by the Global Positioning System (GPS) often depends on the accuracy of the target coordinates provided as aimpoints. However, current geolocation methods using GPS, pointing angles, and terrain elevation are only accurate to 100 m at best, which is inadequate for precision strike. This article discusses an APL-developed technique called Multiple Image Coordinate Extraction (MICE) that can use unmanned air vehicle (or other equivalent) imagery to pinpoint target coordinates to within about a 5-m CEP (circular error probable). By applying principles of photogrammetry to determine the locations and sizes of objects, MICE can be easily integrated into imaging platforms.

(Keywords: Geolocation, Photogrammetry, Rapid targeting, Reconnaissance, UAV.)

INTRODUCTION

Current and anticipated weapons that are guided by the Global Positioning System (GPS) have been designed to have very small delivery CEPs (circular error probable). The limiting factor on the effectiveness of these weapons is often the accuracy of the target coordinates provided as aimpoints. The Laboratory's Strategic Systems Department has developed a technique called Multiple Image Coordinate Extraction (MICE)¹ that can use unmanned air vehicle (UAV) or other equivalent imagery to rapidly determine target coordinates to within a 5-m CEP under most expected operational circumstances.

MICE applies principles of photogrammetry to determine both precise object location and size.

The technique is not platform or sensor specific, and can be easily integrated into imaging platforms using electro-optical or infrared sensors and video or still-camera recordings. It has been implemented in the ground station of the Predator UAV without requiring any modifications or upgrades to the hardware.

Today, UAVs like the Predator can estimate the location of the center point (only) of the video field of view (FOV) to within about a 100-m uncertainty. To do this, the payload operator lines up the target with a set of crosshairs that appear in the center of the video monitor. The estimated location of this single point is then displayed.

The largest contributors to the error in this estimate are poor knowledge of the camera pointing angles, poor knowledge of ground elevation, and errors in the GPS location of the UAV. Coordinates derived in this fashion are insufficient for weapons delivery in most cases.

In contrast, the MICE technique does not depend on knowledge of camera pointing angles or the underlying terrain elevation. The lack of dependence on these quantities eliminates two of the three primary sources of error in the standard approach for UAV target coordinate calculation. With MICE, the UAV position itself becomes the largest contributing error factor in the resulting target location. Any of several proven approaches for improving the UAV GPS-based positions would provide the accurate inputs necessary to achieve target coordinates to within 5 m.

Use of real-time UAV imagery data for target identification and geolocation strongly supports warfighting capabilities against relocatable targets and newly identified threats. The application of MICE, which is based solely on existing UAV sensors and equipment, could result in target coordinates with sufficient precision to support most weapons systems within 10 to 15 min of the first view of a target. Many existing and evolving GPS guided weapons (e.g., Extended Range Guided Munitions, Army Tactical Missile System, Tomahawk, Standoff Land Attack Missile, and GPS-guided bombs and artillery) could benefit from this rapid targeting capability.

Accurate, absolute positioning is one application of MICE. Others include calculations of object size and area layout. These measurements can be critical, particularly for military operations in urban terrain.

CONCEPT OF OPERATIONS

The basic concept of MICE is illustrated in Fig. 1. A UAV, with a GPS/Inertial Navigation System (INS),

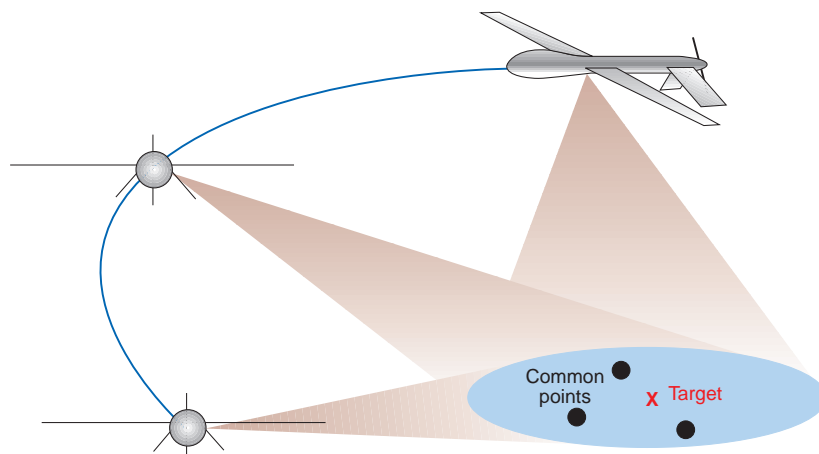


Figure 1. MICE concept of operations. Using at least three images of the target from noncollinear positions, together with the GPS positions of the images and at least three identifiable common points among the images, MICE will calculate the three-dimensional positions of the target and all the common points among the images.

flies through the target area, taking multiple images of the target. The UAV's GPS/INS data and the images are transmitted to the ground control station, where differential corrections can be applied to the UAV positions and MICE processing is performed to extract target coordinates. At least three images of the target from noncollinear positions, along with at least three identifiable common points among the images, will allow the calculation of the three-dimensional positions of the target and all common points among the images.

The target, which will usually be one of the common points, does not need to be centered in the FOV. These common points among the images are not previously surveyed benchmarks or registration points. Almost anything—from a corner of a building to a rock or tuft of weeds—can serve as a common point.

The camera pointing angles are not required as inputs to the calculation, but approximate values can reduce the calculation time by providing a starting point for the MICE algorithm. Similarly, the terrain elevation in the target area is not a required input, since MICE calculates the full three-dimensional geodetic position for each point.

The camera's focal length and the optical center of the sensor plane must be known. These factors are easy to calibrate and need only be done once, or whenever a change to the UAV optics package occurs. Furthermore, the tolerance to which these optical parameters must be known is not very exacting.

For any set of UAV positions and common-point image coordinates, there is only one set of camera angles and three-dimensional positions for the common points that could have generated the observed set of perspective views. The input data are sufficient to solve for these quantities. Errors in the UAV position are the only significant remaining contributor to the error in the resulting coordinates.

Data requirements for MICE consist of three noncollinear images with associated support data. The required support data include the GPS latitude, longitude, and altitude of the UAV (preferably P(Y)-code) when it took each image as well as the optical parameters of the camera. The GPS position data must be accurately synchronized with the imagery; if they are not, an effective error in UAV position (the UAV velocity times the synchronization error) will occur. The use of more than three images will lead to a better solution. It must be possible to identify at least three common points within the imagery.

Knowledge of which GPS satellites are being tracked by the UAV as well as the precise time of fix is necessary to support navigation enhancements such as differential GPS (DGPS) corrections. Additional data that could support performance improvements include more detailed navigation data from the UAV GPS receiver such as carrier phase measurements, tropospheric corrections, pseudorange, etc.

IDENTIFICATION OF COMMON POINTS AMONG IMAGES

To determine the target's coordinates, the operator must select at least three still frames from the UAV video, together with associated UAV position data; more images will increase the quality of the solution. The MICE algorithm requires manual identification of the common points. Only three such points are required, but additional points provide improvement in the solution. If enough points are available, all points need not be visible in all images. Remember, likely common points can be a tuft of vegetation, a rock, some debris, the corner of an object, or various points on the target itself.

Figure 2 is an image of a target from an SSN/UAV demonstration² (discussed in more detail in the last two sections in this article). Several points have been indicated to show the types of features that might be selected by an operator. Note that unless the image is absolutely void of obvious features, it should be easy to identify at least three common points among the image views.

The user interface of the prototype software simplifies the perusal of the images and the selection of the common points. The user can load all related images. Then, after identifying the first common point, the user can proceed with a single keystroke to the next



Figure 2. Target image with common points.

image to enter the corresponding point. This procedure is repeated for each successive image by cycling through the images until all common points have been entered.

The user can zoom in on the imagery to allow fine-tuning of the selected locations. Single keystrokes allow homing on any point and cycling through the imagery at any resolution while maintaining focus on that point. When all data have been entered, the MICE algorithm is run to determine the coordinates of each point. Since the calculations involved are over-determined if more than three images or three common points are used, the calculation residuals can be superimposed on the imagery. The residual values provide an indication that a point might not have been correctly placed. In such a case, the operator could then move the point or delete it from the calculation.

The MICE algorithm can be set to run interactively, updating the solution and redisplaying the residuals every time the operator adds, moves, or deletes a point. Work is currently under way to automate the placement of common points to mitigate operator time and effort.

MATHEMATICS OF THREE-DIMENSIONAL COORDINATE EXTRACTION

The mathematics of image formation and perspective are described in this section. During the imaging process, points in a three-dimensional Euclidean space (x,y,z) are mapped onto a two-dimensional image plane (i,j) . Figure 3 presents a simple case of a particular imaging geometry. Points A, B, and C are mapped into points a, b, and c in the image plane. The light rays from A to a, B to b, and C to c are straight lines that all intersect at a single point, corresponding

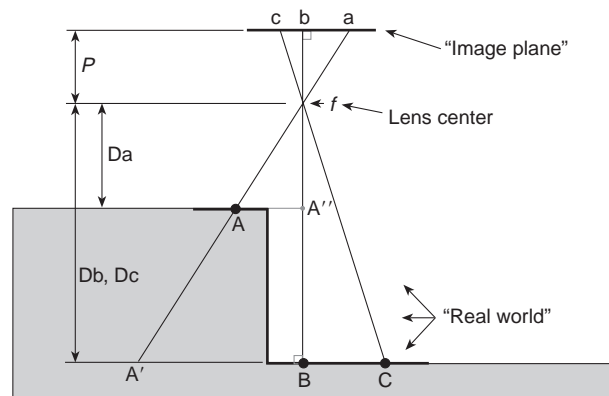


Figure 3. Image formation geometry. D_a , D_b , and D_c are perpendicular distances from f , the lens center, to three-dimensional points A, B, and C. The principal distance P is the perpendicular distance from the center of the lens to the image plane.

roughly to the center of the camera lens. The perpendicular distance from this point to the image plane is called the principal distance (P).

Let the light ray from B to b be perpendicular to the image plane. Point b is defined to be the image center. From simple geometry, note that the triangles (f,b,c) and (f,b,a) are similar to the triangles (f,B,C) and (f,B,A') , respectively, and that (f,B,A') is also similar to (f,A'',A) . This relationship can be written algebraically as

$$\text{length}(b,c)/P = \text{length}(B,C)/Dc \tag{1}$$

and

$$\text{length}(b,a)/P = \text{length}(A,A'')/Da, \tag{2}$$

where $\text{length}(b,c)$ is the distance from point b to point c , Dc is the perpendicular distance from lens center to point C , etc. The image is geometrically similar to the real world, except that lateral distances to points in the image are reduced by a factor proportional to the perpendicular distance from the lens center to the corresponding real-world point.

When the image plane is not parallel to one of the coordinate planes of the three-dimensional world coordinate system, a coordinate rotation must be incorporated into the equations. Let the coordinates of points in a two-dimensional image be i and j . The origin is the upper-left corner of the image, and the (i,j) coordinate system is left-handed to maintain consistency with standard practice in image processing and computer graphics. The coordinates run from $(1,1)$ to (m,n) . The special point designated (i_0,j_0) is the point at which a perpendicular dropped from the lens center would intersect the image plane. This point is the image center (point b in Fig. 3).

Figure 4 illustrates the three-dimensional world coordinate system as well as the angles needed to specify the orientation of the camera. The lens center has the coordinates (x_0,y_0,z_0) . The elevation is defined to be the angle between the x - y plane and the line of sight (perpendicular to the image plane). The azimuth is the angle from the $+y$ axis to the horizontal projection of the line of sight. The rotation angle is the angle from the $+z$ axis, about the line of sight, to the $-j$ axis of the image. The use of the $-j$ axis in this definition is necessary because the image coordinate system is left-handed.

The equations that describe the general mapping from the world coordinates into image coordinates will now be written in matrix form. First, the original (x,y,z) coordinate system is translated so that its origin is at the focal point. It is then rotated so that the new x' - z' plane is parallel to the image plane and the $+z'$ axis is parallel to the $-j$ axis. The new coordinates (x',y',z') of any point (x,y,z) in the original coordinate system are given by

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos(ro) & 0 & -\sin(ro) \\ 0 & 1 & 0 \\ \sin(ro) & 0 & \cos(ro) \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(el) & \sin(el) \\ 0 & -\sin(el) & \cos(el) \end{pmatrix} \cdot \begin{pmatrix} \cos(az) & -\sin(az) & 0 \\ \sin(az) & \cos(az) & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{pmatrix} \tag{3}$$

The mapping from the rotated coordinate system into image coordinates is carried out analogously to the simple case presented in Eqs. 1 and 2. The term y' is now the perpendicular distance from the lens center to the common point. Since the i - j coordinate system is left-handed, a sign correction must be introduced into the mapping. The image coordinates i,j are given by

$$(i - i_0)/P = x'/y' \quad (j - j_0)/P = -z'/y' \tag{4}$$

Solving for i and j produces

$$i = Px'/y' + i_0 \quad j = -Pz'/y' + j_0 \tag{5}$$

These equations are the basis of MICE. Given the camera locations, common-point coordinates, and camera calibration data, the three-dimensional locations of the common points and all of the camera pointing angles can be found using standard nonlinear matrix solution techniques.

PREDICTED ACCURACY

We assessed the predicted MICE target location accuracy using both an error covariance analysis and a Monte Carlo simulation. The covariance analysis can quickly handle a variety of conditions. The Monte Carlo model complements the covariance analysis by providing detailed realizations, showing possible outliers, and confirming the robustness of the MICE algorithm implementation.

The Monte Carlo simulation used three images equally spaced on a 3.3-nmi-radius half-circle centered on the target. Nine common points spanned the FOV. (MICE processing time per Monte Carlo trial was less than 10 s on a Pentium Pro 200-MHz personal computer.) The simulated UAV altitude was 5000 ft. The standard deviation of error in marking

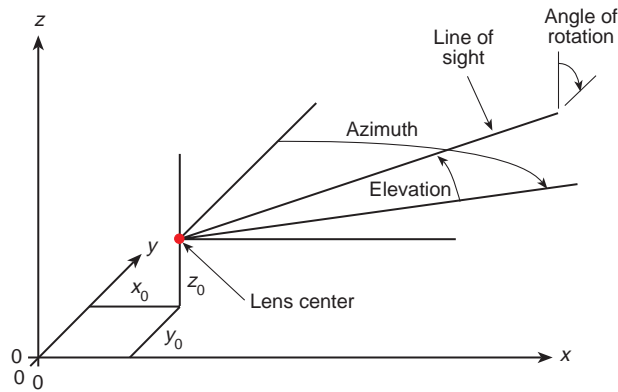


Figure 4. The real-world (three-dimensional) coordinate system and the angles needed to specify the orientation of a camera with respect to that coordinate system. The lens center has the coordinates (x_0, y_0, z_0) .

these common points was assumed to be 0.5 pixel, the camera location uncertainties were assumed to have a 1.5-m standard deviation, and the errors in the pointing angle readouts were assumed to have a 2° standard deviation. The input errors were assumed to be Gaussian distributed, with zero mean values. The resulting horizontal and vertical errors of 1000 Monte Carlo trials are shown in the cumulative histogram in Fig. 5, where the resultant median (50%) horizontal and vertical errors in target location were less than 4 m, and the maximum errors were less than 14 m.

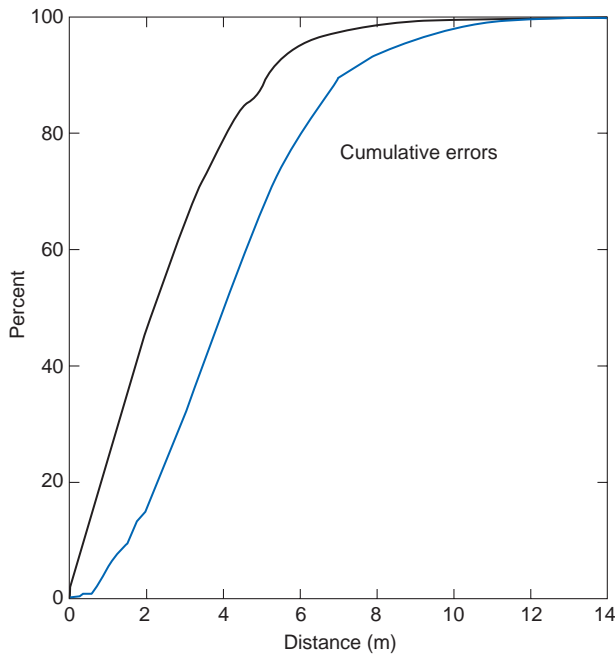


Figure 5. MICE targeting errors from a Monte Carlo assessment (blue curve = horizontal errors, black curve = vertical errors).

The simple case was also examined via a covariance analysis. A 10% error was introduced into the values of the optical parameters (focal length and optical center) to illustrate that the results can be relatively insensitive to the camera calibration.

The predicted accuracy from the covariance analysis is presented in Table 1, which shows that the expected accuracy is almost completely insensitive to the FOV/focal length of the camera used to acquire the imagery. The projected target location accuracy when using a camera with a 17° FOV is virtually the same as that predicted for a camera with a 0.3° FOV telephoto lens. The only limitation on FOV is that the accuracy of geolocation will be limited by the ground sample distance of a single pixel. That is, if a single pixel covered 6 m on the ground, it would usually be difficult to locate any point to better than that granularity. This effect is not likely to be a consideration when using most UAV imagery.

The targeting accuracy is primarily dependent on the accuracy of the UAV camera positions. When the UAV positions are limited to simple, raw P(Y)-code (military GPS, accurate to 12–14 m), the resulting target coordinates will be accurate to about 12 to 14 m. If the UAV positions are known to 1 to 2 m by improved GPS or ground-based differential GPS (DGPS), as discussed in the following section, the derived target coordinates can be as good as 3 to 5 m.

DATA QUALITY

As we have already noted, several factors related to data quality affect the accuracy of the target coordinates generated by MICE. The primary factors, which are detailed in the following paragraphs, are the accuracy of the UAV GPS data (including the timing errors between the imagery and the support data), the image quality, and the relative geometry from which the multiple images are acquired.

Table 1. Predicted MICE target location accuracy based on covariance analysis.

FOV (deg)	Target accuracy CEP (m)	
	GPS-P(Y)	DGPS
17.0	14.6	4.0
1.7	14.4	3.3
0.3	14.4	3.3

Note: CEP = circular error probable; see text for discussion of GPS-P(Y) and DGPS.

GPS Enhancement

The uncertainty in the UAV position is the primary source of error in MICE. Enhancement to UAV navigation such as the application of DGPS or completion of the GPS Accuracy Improvement Initiative could reduce the error to much lower levels than even the current P(Y) code. Table 2 compares the most promising approaches.

Standard differential navigation consists of the application of commercial off-the-shelf components and requires only the receiver on the UAV and a stationary GPS base station to monitor variations in the GPS signals. The corrections are done in real time and are calculated and applied at the ground station. The UAV requires no modifications. This approach restricts the range between the UAV and ground station to within direct line of sight.

There are other methods of GPS accuracy improvement that are not as operationally restrictive. The application of wide-area DGPS (WADGPS) supports up to a 1000-nmi reference/receiver separation. When the GPS Accuracy Improvement Initiative is realized, any P(Y) code-capable receiver should be able to support a 2- to 3-m accuracy worldwide. WADGPS has been used during field tests and has provided the navigation accuracies shown in Table 2.

Image Quality Improvement

A standard interlaced video image consists of two subframes taken 1/60th of a second apart. Each subframe contains every other line of the full image. Because of the time delay, there is a mismatch of the imagery content between subframes. This mismatch takes the form of a relative displacement (both horizontal and vertical) between the subframes, which can be as large as 3 or 4 pixels in each axis. This shift is

due to the motion of the UAV and to the random jitter of the camera stabilization system during the 1/60th of a second interval.

Image processing software was developed at APL to correct the UAV imagery for these horizontal/vertical shifts. Without this compensation, it would have been impossible to achieve the accuracy for the common-point coordinates necessary for MICE. Figure 6a shows an enlarged subset of one of the images acquired during the SSN/UAV demonstration.³ The edges of the features are jagged; corners and small features are obscured. Accurate, consistent location of common points using such an image would be difficult. Figure 6b shows the same image after processing to realign the subframes. Edges of objects are now sharp, and details are much easier to discern. This subframe realignment serves only to reduce the impact of the interlace. The degradation could be eliminated entirely by the use of a progressive scan video camera, which exposes both subframes simultaneously.

Geometrical Considerations

The accuracy of the target locations generated by MICE depends on the geometry with which the multiple images are obtained. MICE works best when the image positions do not lie along (or near) a straight line and when the lines of sight to the target subtend as large an angle as possible about the target. Figure 7 shows a notional geometry of three different possible data sets from the SSN/UAV demonstration.

For the first data set, the blue squares represent the UAV locations from which each of three images would be taken. The vector on each symbol shows the look angle of the payload camera. Note that the images need not be taken from points having equal range to the target. This geometry is less than ideal since the track

is relatively collinear, thereby compromising the accuracy of target coordinates. The total angle subtended about the target is just under 90°, which is the minimum for adequate performance. The second notional geometry, shown in red, is not collinear, but all three images are taken from one side of the target. The total angle subtended about the target is very small. This geometry will generate a poor target solution. The third geometry, shown in green, is also not collinear. In this case, however, the total angle subtended about the target is approximately 180°. If the UAV were high enough that the look-down angle to the target

Table 2. GPS accuracy options.

GPS operating mode	Range to UAV (nmi)	Accuracy (m)
Commercial GPS	N/A	45–50
Military GPS	N/A	8–15
Commercial DGPS	<55	3–5
Military DGPS	<270	1–2
WADGPS, tuned ephemeris	<1000	1–2
GPS Accuracy Improvement Initiative	N/A	2–3

Note: N/A = not applicable; WADGPS = wide-area differential GPS.

exceeded about 30°, this would be an ideal geometry for generating accurate target coordinates.

MICE TARGET LOCALIZATION WITH SSN/UAV DEMONSTRATION DATA

The demonstration of MICE target localization capability³ was under certain constraints. Because it was conducted on a noninterference basis with primary SSN/UAV demonstration objectives, the data collected for MICE had limitations in quantity, camera location accuracy, image data quality, and flight geometries. The MICE image quality and flight geometry discussed previously used these SSN/UAV data. Data for just two MICE targets were collected, with the UAV at an 8000-ft altitude and a 1.5- to 3-nmi horizontal range from the targets.

A GPS base station was set up during SSN/UAV demonstrations to support an accurate survey of ground targets to provide differential corrections to UAV GPS data. The original UAV camera location data were only C/A code GPS (civilian GPS) data. Therefore, 45 to 50 m of error due to the C/A code position data could be expected without DGPS corrections.

The resulting MICE target locations with the original GPS position data were separated horizontally from the actual, surveyed positions of the two targets by 50 and 70 m, respectively. Differential corrections were applied to the UAV GPS data for one target. The MICE location for this target then improved to within 10 m horizontally. Note that the 10-m result included some camera location error due to timing synchronization errors between the imagery and support data.

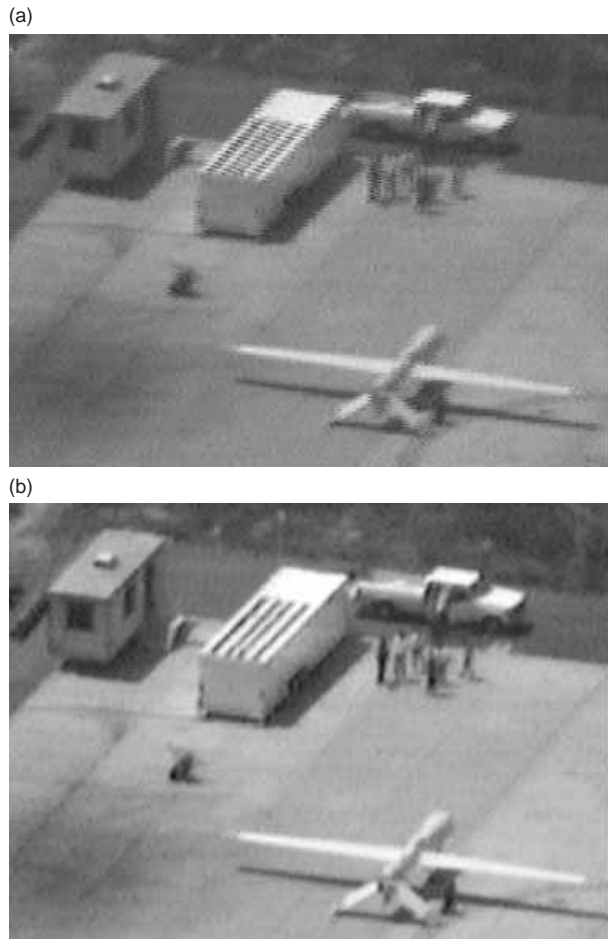


Figure 6. Enlarged image region (a) exhibiting subframe mismatch and (b) after processing.

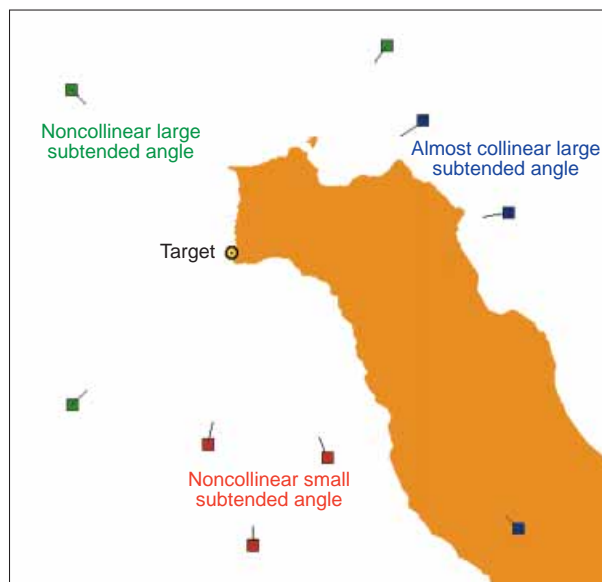


Figure 7. Alternate imaging geometries. The ideal imaging geometry for MICE is noncollinear, with large angle subtended about the target. Distance to the target and altitude may vary. The green squares illustrate a favorable imaging geometry, the blue squares are too nearly collinear, and the red squares subtend too small an angle.

SUMMARY

MICE, an algorithm for calculating geodetic coordinates and sizes of objects using remotely sensed imagery, requires only several images and associated camera locations. Resultant target location errors will be of about the same magnitude as the errors in the UAV GPS positions.

MICE is part of several Strategic Systems Department programs. The fundamental technology, developed for another application, was first presented in a 1993 department report.¹ MICE was applied³ to data acquired during the SSN/UAV demonstration,² in which it was able to locate a target to better than a 10-m accuracy from a standoff range of 3.3 nmi. Work on MICE targeting is continuing as part of the Navy Tactical Control System Program.

An Independent Research & Development (IR&D) project is currently under way for advanced applications of MICE. It will address the difficult,

high-priority problem of automated common-point placement under various operational conditions. One of the authors has already developed an automated common-point placement algorithm that is effective under benign conditions. Applied to imagery from relatively flat to rolling terrain, this algorithm can generate correspondences to a 0.1-pixel accuracy when the perspectives between the images are fairly similar. Other IR&D topics apply MICE to area mapping and to local measurements of size and relative distance.

MICE has potential applications for rapid, precise targeting against emerging targets; area surveillance for pre- and postbattle assessment; area mapping; and local measurements of size and separations for military operations in urban terrain.

REFERENCES

- ¹Criss, T. B., *Multiple Image Mensuration*, JHU/APL SSD/POR-93-6836, Laurel, MD (Aug 1993).
- ²Rau, J. L., and Ball, R., "Demonstration of SSN/UAV Interoperability," in *Proc. Association of Unmanned Vehicle Systems International* (15–19 Jul 1996).
- ³Criss, T. B., Levy, L. J., and Rau, J. L., "Precise Target Localization Using UAV Data," in *Submarine Technology Symposium*, JHU/APL, Laurel, MD (1997).

THE AUTHORS



THOMAS B. CRISS received his Ph.D. in physics from the University of Texas at Austin in 1975 and joined APL in 1976 as part of the Strategic Systems Department. He has extensive experience in image processing, signal processing, position reference systems, photogrammetry, and numerical and optimization techniques. Dr. Criss has collaborated with researchers at The Johns Hopkins University Medical School on the development of algorithms for optimizing delivery of radiation to treat brain tumors. He has taught graduate-level courses in image processing and general relativity at the JHU Whiting School of Engineering. His e-mail address is tom.cris@jhuapl.edu.



MARILYN M. SOUTH received her Ph.D. in quantum chemistry from The Johns Hopkins University in 1975. She joined APL in 1977 and is currently a mathematician in the Systems Development and Operational Support Group of SSD. Dr. South has worked on the applications of computer-aided analysis to underwater acoustics, missile flight simulations, image processing, and MICE. Her e-mail address is marilyn.south@jhuapl.edu.



LARRY J. LEVY received his Ph.D. in electrical engineering from Iowa State University in 1971. He is currently Chief Scientist of the Strategic Systems Department at APL. Dr. Levy has worked on applied Kalman filtering for over 30 years, was the co-developer of the GPS translator concept in SATRACK (a GPS-based missile tracking instrumentation system), and was instrumental in developing the end-to-end methodology for the Trident II accuracy evaluation. He teaches graduate courses in Kalman filtering and system identification at the JHU Whiting School of Engineering and conducts seminars on these subjects for Navtech seminars. His e-mail address is larry.levy@jhuapl.edu.