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ISAR Motion Compensation using the registration-restoration-fusion method

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Abstract

A new method is developed to perform target translational and rotational motion compensation for ISAR imaging. The method is based on a registration-restoration-fusion technique. This technique provides an efficient method to resolve the image smearing caused by the time-varying behavior of the target scattering centers and leads to a well-focused ISAR image. The basic idea is to use the nearest neighbor method to obtain control points and estimate motion parameters from two or more candidate images. The registration processes use these estimated motion parameters to remove both translational and rotational motion. The restoration process may be used to eliminate the blur that is induced by the registration process. Furthermore, the fusion of two registered images before or after restoration processing could be used to generate the focused ISAR image. This proposed method has been successfully applied to both experimental and simulated ISAR data.

Résumé

Une nouvelle méthode est élaborée pour effectuer la compensation du mouvement de translation et de rotation de la cible, aux fins de l'imagerie ISAR. Cette méthode est basée sur une technique de cadrage-restitution-fusion. Cette technique constitue une méthode efficace pour résoudre la bavure de l'image causée par le comportement variable dans le temps des zones de diffusion de la cible et donne lieu à une image ISAR bien focalisée. Le concept de base consiste à utiliser la méthode du voisin le plus proche pour obtenir des points de contrôle et à estimer les paramètres de mouvement à partir de deux ou plusieurs images candidates. Les processus de cadrage utilisent ces paramètres de mouvement estimés pour supprimer tant le mouvement de translation que le mouvement de rotation. Le processus de restitution peut être utilisé pour éliminer le flou introduit par le processus de cadrage. Finalement, la fusion de deux images cadrées, avant ou après le processus de restitution, pourrait être utilisée pour générer l'image ISAR focalisée. Cette méthode proposée a été appliquée avec succès à des données ISAR tant expérimentales que simulées.

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Executive summary

Inverse synthetic aperture radar (ISAR) imaging is an effective way to acquire high resolution images of targets of interest at long range and as such is an irreplaceable tool in the task of non-cooperative target recognition (NCTR) of both ships and aircraft. The Canadian Air Force is currently upgrading the fleet of CP-140 Aurora maritime patrol aircraft to possess NCTR through ISAR in order to increase the capability of the Canadian Forces in both sovereignty patrols of Canadian territory and the protection of the Canadian Patrol Frigates and allied ships operating abroad as a coalition. The United States Navy's equivalent aircraft, the P-3 Orion, currently possesses this capability. Therefore, effective ISAR imaging will have a real impact in the decision making process in future military operations involving both Canadian and American forces.

In real-world ISAR imaging scenarios, the target is often engaged in complicated manoeuvres that combine translational and rotational motion. Significant blurring can result in the ISAR image unless a good motion compensation method is implemented. Therefore, a motion compensation method to focus ISAR images is of paramount importance to military and intelligence operations.

In this report a new method is developed and proposed to perform target translational and rotational motion compensation for ISAR imaging. The method is based on a registration-restoration-fusion technique. The basic idea is to use the nearest neighbor method to obtain control points and estimate motion parameters from two or more candidate images. The registration processes use these estimated motion parameters to remove both translational and rotational motion. The restoration process may be used to eliminate the blur that is induced by the registration process. Furthermore, the fusion of two registered images before or after restoration processing could be used to generate the focused ISAR image. This proposed approach has been successfully applied to both experimental and simulated ISAR data. This report provides the preliminary ground work for this challenging field of research.

Results also show that if a target is moving smoothly, standard motion compensation generates a clear image of the target by using the conventional Fourier transform methods. However, when a target performs complex motion such as perturbed random motions, standard motion compensation is not sufficient to generate an acceptable image. In this case, the registration-restoration-fusion motion compensation method provides an efficient candidate to resolve the image smearing caused by the time-varying behavior and leads to a well-focused ISAR image. This study

also adds insight into the distortion mechanisms that affect the ISAR images of a target in motion.

T. Thayaparan; 2006; ISAR Motion Compensation using the registration-restoration-fusion method; DRDC Ottawa TM 2006-131; Defence R&D Canada – Ottawa.

Sommaire

L'imagerie du radar à synthèse d'ouverture inverse (ISAR) est une façon efficace d'acquérir des images à haute résolution de cibles d'intérêt à longue distance et comme telle est un outil irremplaçable dans la tâche de reconnaissance de cible non coopérative (NCTR) à la fois de navires et d'aéronefs. La Force aérienne du Canada est en train de mettre à niveau la flotte d'avions de patrouille maritime CP-140 Aurora en les dotant de la fonction NCTR au moyen de l'ISAR afin d'augmenter la capacité des Forces canadiennes tant dans les patrouilles de protection de la souveraineté du territoire canadien que dans la protection des frégates de patrouille canadiennes et des navires alliés faisant partie d'une coalition à l'étranger. L'aéronef équivalent de la marine américaine, le P-3 Orion, est déjà doté de cette capacité. Par conséquent, une imagerie ISAR efficace aura une forte incidence sur le processus de prise de décisions lors d'opérations militaires futures effectuées par des forces canadiennes et américaines.

Dans les scénarios d'imagerie ISAR en conditions réelles, la cible se trouve souvent à effectuer des manIJuvres complexes qui combinent le mouvement de translation et le mouvement de rotation. Un flou considérable peut se produire dans l'image ISAR, à moins qu'une bonne méthode de compensation du mouvement ne soit mise en IJuvre. Par conséquent, une méthode de compensation du mouvement permettant de focaliser les images ISAR est primordiale pour les opérations militaires et de renseignement.

Le présent rapport porte sur l'élaboration d'une nouvelle méthode proposée pour effectuer la compensation du mouvement de translation et de rotation de la cible, aux fins de l'imagerie ISAR. Cette méthode est basée sur une technique de cadrage-restitution-fusion. Le concept de base consiste à utiliser la méthode du voisin le plus proche pour obtenir des points de contrôle et à estimer les paramètres de mouvement à partir de deux ou plusieurs images candidates. Les processus de cadrage utilisent ces paramètres de mouvement estimés pour supprimer tant le mouvement de translation que le mouvement de rotation. Le processus de restitution peut être utilisé pour éliminer le flou introduit par le processus de cadrage. Finalement, la fusion de deux images cadrées, avant ou après le processus de restitution, pourrait être utilisée pour générer l'image ISAR focalisée. Cette méthode proposée a été appliquée avec succès à des données ISAR tant expérimentales que simulées. Le présent rapport jette les bases préliminaires de ce domaine de recherche riche en défis.

Les résultats montrent aussi que, si une cible se déplace uniformément, la compensation standard du mouvement génère une image claire de la cible en faisant appel aux méthodes de transformée de Fourier classiques. Cependant, lorsqu'une cible décrit des mouvements complexes, tels que des mouvements aléatoires perturbés, la compensation standard du mouvement ne suffit pas pour générer une image acceptable. Dans ce cas, la méthode de compensation du mouvement par cadrage-restitution-fusion constitue une option efficace pour résoudre la bavure de l'image causée par le comportement variable dans le temps et donne lieu à une image ISAR bien focalisée. De plus, la présente étude donne une meilleure idée des mécanismes de distorsion qui influent sur les images ISAR d'une cible en mouvement.

T. Thayaparan; 2006; ISAR Motion Compensation using the registration-restoration-fusion method; DRDC Ottawa TM 2006-131; R & D pour la défense Canada – Ottawa.

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1 Introduction

Inverse synthetic aperture radar (ISAR) imaging is an effective way to acquire high resolution images of targets of interest at long range and as such is an irreplaceable tool in the task of non-cooperative target recognition (NCTR) of both ships and aircraft [1-3]. In real-world ISAR imaging scenarios, the target is often engaged in complicated manoeuvres that combine translational and rotational motion. Significant blurring can result in the ISAR image [2-4], unless a good motion compensation method is implemented. Therefore, a motion compensation method to focus ISAR images is of paramount importance to military and intelligence operations.

One significant problem with ISAR image formation is the assumption of time invariance of the Doppler frequency used to resolve the image in the cross range. Time variant Doppler becomes present in an ISAR signal when an aircraft is manoeuvring or a ship is pitching and rolling during the coherent processing interval, and is typically referred to as motion error. Using the fast Fourier transform (FT) to cross range focus an image with this motion error present will cause extensive blurring in the cross-range and leave the image unrecognizable even to the most experienced ISAR operators [2-3].

One proven method of motion compensation is the adaptive joint time-frequency (AJTF) algorithm [2-3]. The existing Adaptive Joint Time Frequency (AJTF) based motion compensation technique performs Doppler tracking to individual scatterers via an AJTF projection technique. After maximizing the projection of the phase function to a set of basis functions in the time-frequency plane, the Doppler frequency drift of the strongest scatterer in the range bin is automatically tracked out and the multiple Prominent Point Processing (PPP) scheme is implemented to eliminate both the translational motion error and rotational motion non-uniformity [2-3]. However, this algorithm is not without significant weaknesses of its own. One of the problems is that the computational burden of the exhaustive search used to extract the motion compensation parameters is quite large, which limits its usefulness in an operational situation. Other promising alternatives for the motion compensation are techniques that are based on time-frequency analysis methods [4-6].

A new method is developed in this report to perform target translational and rotational motion non-uniformity compensation for ISAR imaging. The method is based on a registration-restoration-fusion technique. This report contributes another new approach to focus distorted ISAR images and contributes analysis that should add in developing a better picture of the motion compensation in ISAR imaging. The proposed approach has been successfully applied to both experimental and simulated ISAR data.

2 Registration-Restoration-Fusion Motion Compensation Procedure

The image registration, restoration and fusion are the basic image processing operations in remote sensing. A recorded image is likely to be degraded by sensor sampling. The purpose of this kind of image processing technique is to operate on the degraded image to obtain an improved image. Since it is similar to ISAR motion compensation, new registration, restoration, and fusion techniques that are suitable for ISAR motion compensation have been developed and integrated into one toolbox to make this motion compensation operation flexible and convenient. The motion compensation process includes three main steps: registration, restoration, and fusion [7-9].

2.1 Image Registration

The image registration is the process of matching two images (reference and input images) so that corresponding coordinate points in the two images refer to the same physical region of the scene being imaged. The accurate sub-pixel registration between two ISAR imaging frames is key to the success of motion compensation. To perform point scatter registration, a method named the 'nearest neighbor method' is developed to search for corresponding control points from two candidate images [7-8]. The method is to set a window around the position of a point scatterer that is found in the reference image. The position of point scatterers in the input image is determined on the chosen window. The registration parameters (scale and rotation angle) can be determined by the position relationship of two sets of control points. Then the registration methods, including the second, third, and fourth order polynomial methods, the linear conformal method, the affine method, and the projective and piecewise linear methods, are investigated and compared to generate the registered image [7-9]. A minimum number of control points are needed for these registration methods. For example, six point scatterers are needed for the second order polynomial method and three point scatterers for the affine registration method. The second order polynomial method is used in this report.

2.2 Blur Estimation and Restoration

The blur estimation is a key step for image restoration. It takes an image that has been degraded by linear blur, which is an image that has been convolved with some

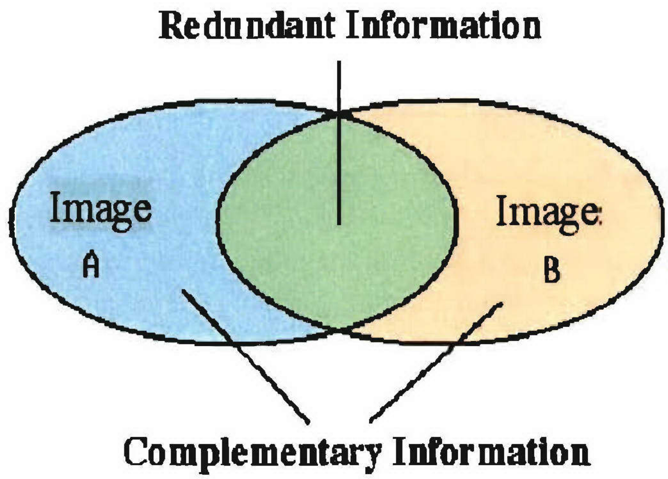


Figure 1: *The concept of image fusion.*

point-spread function (PSF), and returns an estimate of the original image [10-11]. The PSF can be specified as a mask whose dimensions are smaller than those of the image, or it can be specified as a mask whose dimensions are identical to those of the image. The toolbox provides automatic blur estimation, which can be accessed from the restoration toolbox interface. If the blur function exists, it could be used in the restoration operation directly.

The restoration process can be used after the registration process to reduce blur. It can also be used before the registration to separate two adjacent point scatterers in order to generate accurate motion parameters. Five restoration methods have been evaluated in this study: least squares restoration, resolution-to-noise trade-off restoration, Lucy-Richardson restoration, regularized filter algorithm, and Wiener filter algorithm [12-13]. The Lucy-Richardson restoration method has been used in this report.

2.3 Fusion

Finally, the fusion process is applied to two or more registered ISAR images in order to improve the reliability and capability of target recognition [5-6]. The reason for this is that the fused image has more complete target information than the input images. The fused image is produced from two or more input images by utilizing redundant and complementary information as shown in Figure 1.

It should be emphasized here that there are several methods that have been developed for registration, restoration, and fusion in image processing. It is not the objective of this report to perform trade-off studies of the individual methods. Rather, the objective is to demonstrate the proposed approach by using the experimental and simulated ISAR data and provide some insight as to how the registration-restoration-fusion approach can be used for focusing ISAR images. This report develops the preliminary ground work for this challenging field of research.

3 Results

We demonstrate the application and effectiveness of the registration-restoration-fusion motion compensation method with simulated and measured experimental radar data.

3.1 Simulated Data

To gain a better physical insight into the scattering phenomenon of an aircraft's ISAR image, an aircraft can be assumed to be composed of a set of point scatterers on a two-dimensional plane. Each scattering point on the aircraft does not represent any geometric point on the target but rather a combination of scattering sources that return a radar echo. A two-dimensional model of an aircraft's scattering centres is sufficiently adequate to analyze the ISAR images of aircraft.

In this simulation it is assumed that the target contains six microwave corner reflectors (i.e., scatterers) to simulate the distorting effect that could occur in ISAR images. A picture of the target is shown in Figure 2. The center frequency of the radar is 9 GHz and the bandwidth is 300 MHz. A total of 30 range cells and 50 cross-range cells are used for the imaging. Figure 3a shows the image from the simulated data, without any added motion error, as a reference for comparison. This figure illustrates the undistorted ISAR image when the target is uniformly rotating at a constant rate of 3 degrees/second. Since there are no random motions, we can use the conventional Fourier transform (FT). That is, we take a series of one-dimensional Fourier transforms across the target. As expected, the image is well-focused.

Then perturbed random motion (or motion error) is injected into the simulation. That is, in addition to the uniform (3 degrees/second) rotation perturbed random motion through a 'sine-drive' is injected by adding an additional sine wave to the motion. The resultant rotational motion will then be non-uniform. It should be noted here that the rotational motion of the target is confined to a two-dimensional plane during the coherent processing interval. Figures 3b illustrates the distorted image obtained by using the conventional Fourier transform. In this case, the perturbed oscillation is 1 Hz. The figure clearly shows that the image is severely distorted, which means that the target image itself contains much rotational error. The image is smeared along the cross-range direction. This is because of the target's complex motion due to perturbed random motion during the entire coherent processing interval. The conventional radar imaging that uses the Fourier transform,

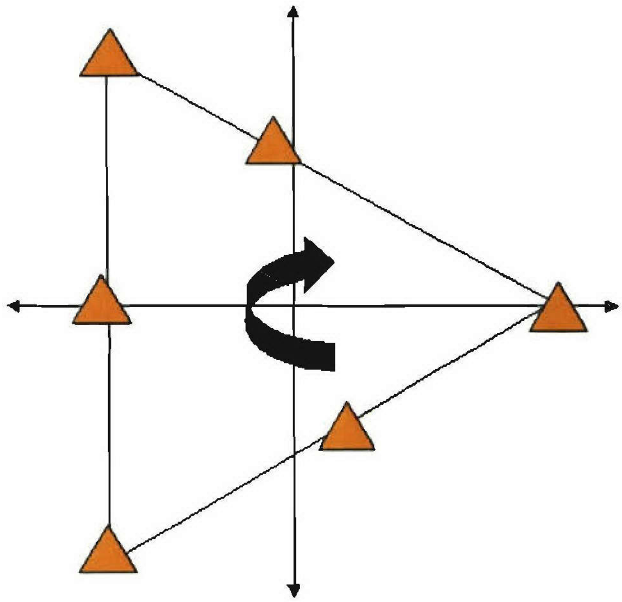
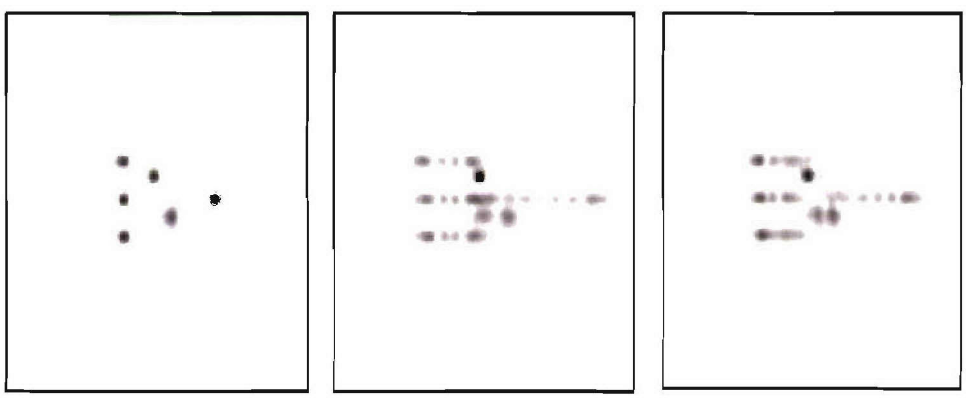


__Figure 2:__ A picture of the simulated target consisting of six simulated corner reflectors.



(a) (b) (c)

__Figure 3:__ (a) ISAR image using FT. The 6 reflectors are uniformly rotating at a constant rate of 3 degrees/second. The data has no random error. This image is used as a reference for comparison; (b) Distorted ISAR image using FT. The data has random motion error; (c) Distorted ISAR image using FT. The data has random motion error.

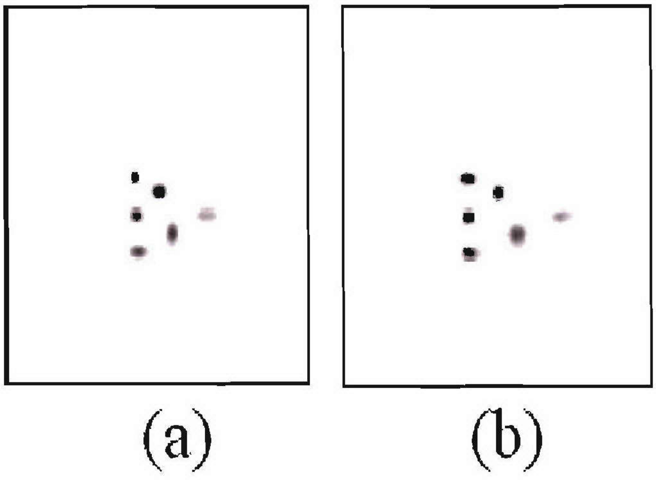


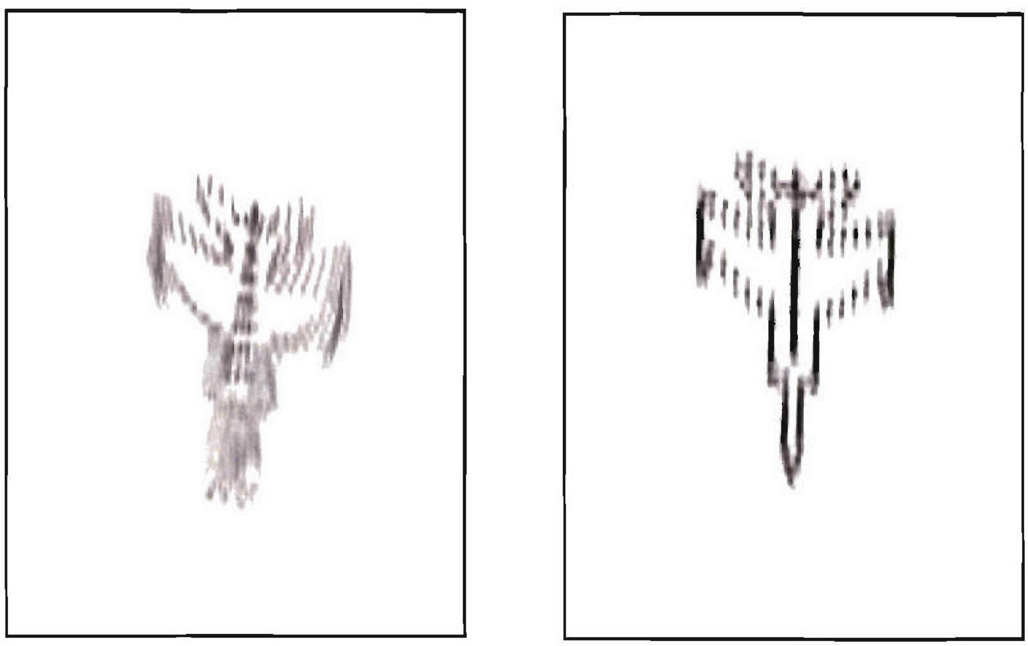
Figure 4: Focused ISAR image using the registration-fusion motion compensation algorithm. (a) Motion compensated image of the data in Figure 4(b) and (b) Motion compensated image of the data in Figure 4(c).

which works well for uniform rotational motion, cannot be directly applied to the perturbed target.

The registration-restoration-fusion method is then applied to these data. Figure 4a illustrates the final image after the registration, restoration, and fusion procedures. All the scatterers are well focused in their individual range and cross-range cells. This implies that all the quadratic phase terms are eliminated.

Figure 3c illustrates another example of a distorted image due to perturbed random motion error. The image is poorly focused and the image of each scatterer is severely smeared. In this case, the perturbed oscillation is 0.57 Hz. Figure 4b shows that the registration-restoration-fusion motion compensation method successfully eliminates the quadratic phase terms and shows a well-focused ISAR image. In Figure 3a, the image from the simulated data without any added motion errors is shown as a reference for comparison. We can see that the motion-compensated image achieves the same sharpness as the reference image.

Another example is a simulated MIG25 aircraft. The radar centre frequency is 9 GHz and the bandwidth is 500 MHz. A total of 64 range cells and 256 cross-range cells are used for the imaging. The FT-based image of the radar target is depicted in Figure 5a. The radar image obtained by using the registration-restoration-fusion



(a) (b)

Figure 5: *(a) FT-based ISAR image formation and (b) Registration-restoration-fusion based ISAR image formation.*

approach is presented in Figure 5b. These results suggest that improvement of the radar image can be achieved by using the registration-restoration-fusion approach.

3.2 Experimental Data

A 5m by 5m delta-wing apparatus was constructed to simulate a full size target. A picture of the target is shown in Figure 6. Six corner reflectors were mounted on the apparatus to simulate the major scattering centres of the target. These six corner reflectors were set to oscillate on their own at a controlled rate to simulate the fluttering effect from aircraft parts or mounted stores on aircraft. The apparatus was mounted on a rotating table that can produce rotational motions at a controlled rate. These rotational motions were confined to a two-dimensional plane. Therefore, data from this pseudo point-source target permits an easier and a more definitive analysis of the residual motion effects on ISAR images.

In this section, a set of real data is used to demonstrate the effectiveness of the registration-restoration-fusion motion compensation procedure. This experimental data set is particularly useful since the entire data set consists of 60,000 pulses in the cross-range. The data covers 30 seconds for which one second of data corresponds to 2000 samples in the cross-range. Therefore 30 seconds of data corresponds to 60000 samples in the cross-range. There are 41 down range bins. The 60,000 pulses can be cut into different size imaging intervals with each of these intervals displaying a different amount of error.

The images shown in the examples are from the time-frequency based imaging. The image at the time of the first, second, and third second are taken to demonstrate the motion compensation process described in the previous section. The results are shown in Figure 7. In this figure, the image at the time of the first second in Figure 7a is a reference image. The image at the time of the third second in Figure

Table 1: *The position of the point scatterers in the reference image, input image, and registered image.*

Reference Image (Base Points)	Input Image (Input Points)	Registered Image
25 11	24 9	25 11
17 24	17 26	17 24
26 21	26 20	26 21
27 30	27 31	27 30
23 29	23 29	23 29
21 18	21 18	21 18

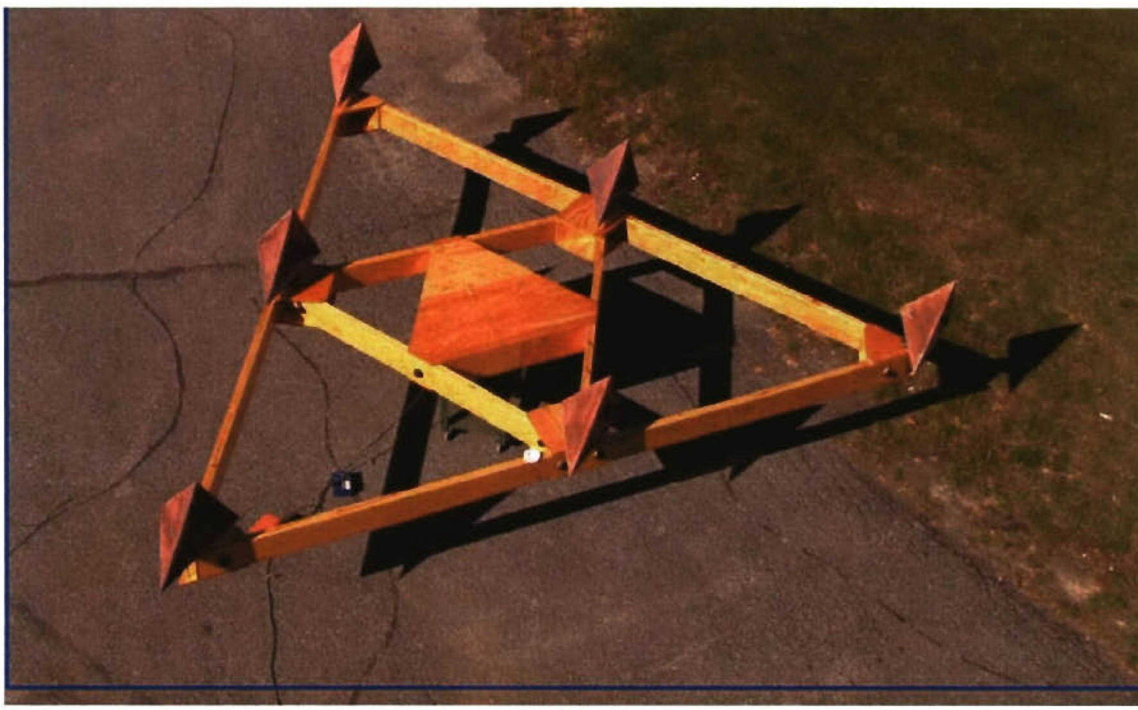


Figure 6: *A picture of the target motion simulator experimental apparatus.*

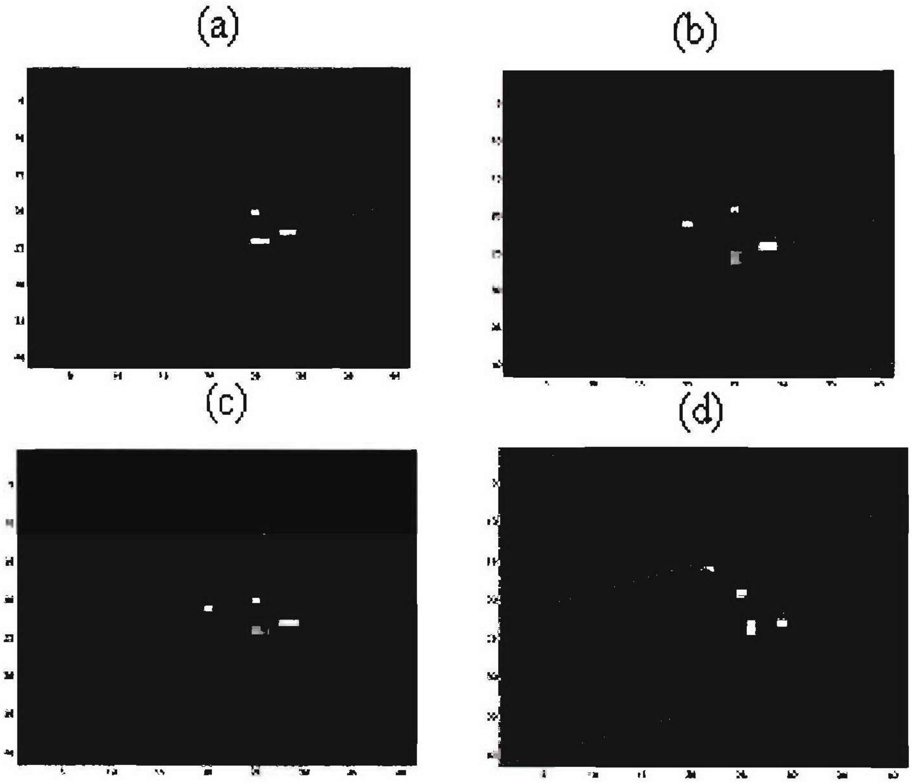


Figure 7: *The results from frame 12 and 13 of real data. (a) Reference image; (b) input image; (c) registered image; (4) fused image.*

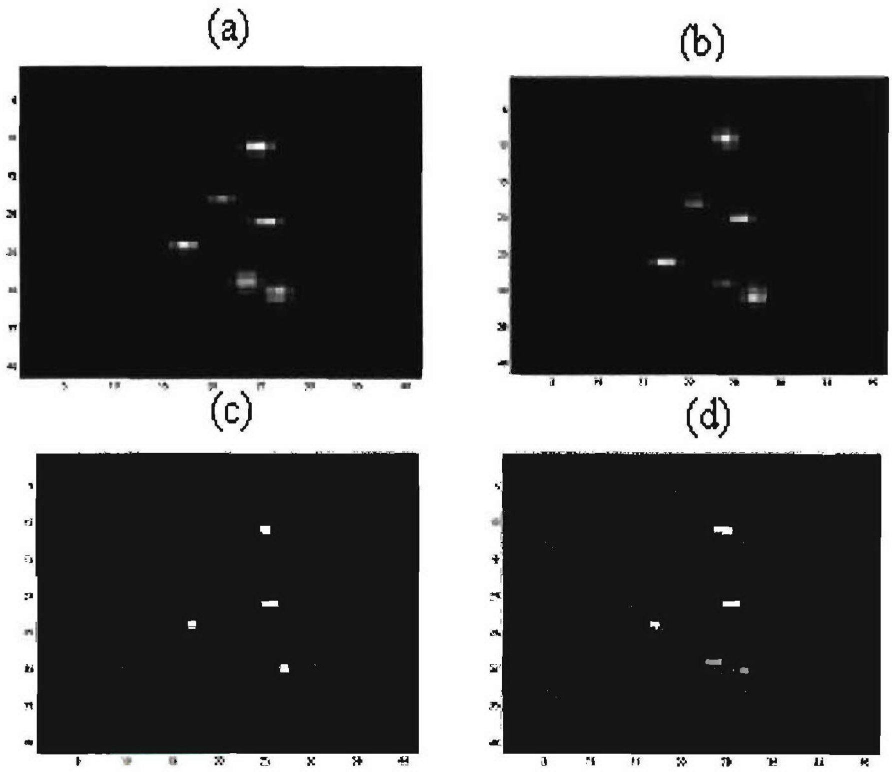


Figure 8: *The results from frame 1 and 3 of real data. (a) Reference image; (b) input image; (c) registered image; (4) fused image.*

Table 2: *The position of the point scatterers in the reference image, input image, and registered image.*

Reference Image (Base Points)	Input Image (Input Points)	Registered Image
25 24	25 26	25 24
28 23	28 24	28 23
25 20	25 19	25 20
20 21	20 21	20 21
21 18	21 16	21 18
19 25	19 27	19 25

7b is the input image and will be registered to the reference image. The image in Figure 7c is the registration result. The corresponding positions of control points and the positions of point scatterers of the registered image are shown in Table 1. The result shows that the registration method gives good performance. The fused image is shown in Figure 7d.

Figure 8 shows the results of a second example corresponding to the 12th and the 13th second of the data. The 12th second image in Figure 8a is considered as the reference image, and the 13th second image in Figure 8b is the input image that is registered to the reference image. The result is shown in Figure 8c, and the corresponding positions of the point scatterers are shown in Table 2. The processing also gives good performance. The fused image is shown in Figure 8d and is more focused than the original image.

4 Conclusion

A motion compensation method based on a registration-restoration-fusion image processing approach has been proposed to perform ISAR motion compensation. The registration-restoration-fusion motion compensation method has been applied to the simulated and measured experimental ISAR data sets. The results demonstrate that the registration-restoration-fusion motion compensation approach gives good performance and generates focused ISAR images. In the future, the registration-restoration-fusion-based motion compensation method could be used to estimate parameters of motion, and the estimated parameters could be applied to multiple prominent point-processing models. This report provides the preliminary ground work for this challenging field of research.

Results also show that if a target is moving smoothly, standard motion compensation generates a clear image of the target by using the conventional Fourier transform methods. However, when a target performs complex motion such as perturbed random motions, standard motion compensation is not sufficient to generate an acceptable image. In this case, the registration-restoration-fusion motion compensation method provides an efficient candidate to resolve the image smearing caused by the time-varying behavior and leads to a well-focused ISAR image. This study also adds insight into the distortion mechanisms that affect the ISAR images of a target in motion.

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(U) A new method is developed to perform target translational and rotational motion compensation for ISAR imaging. The method is based on a registration-restoration-fusion technique. The basic idea is to use the nearest neighbor method to obtain control points and estimate motion parameters from two or more candidate images. The registration processes use these estimated motion parameters to remove both translational and rotational motion. The restoration process may be used to eliminate the blur that is induced by the registration process. Furthermore, the fusion of two registered images before or after restoration processing could be used to generate the focused ISAR image. This proposed method has been successfully applied to both experimental and simulated ISAR data.

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ISAR
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Time-Frequency Analysis
Restoration
Fusion
Target Detection
Fourier Transform
Doppler Processing
Image Analysis

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