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Motion correction for passive radiation imaging of small vessels in ship-to-ship inspections

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ABSTRACT

Passive radiation detection remains one of the most acceptable means of ascertaining the presence of illicit nuclear materials. In maritime applications it is most effective against small to moderately sized vessels, where attenuation in the target vessel is of less concern. Unfortunately, imaging methods that can remove source confusion, localize a source, and avoid other systematic detection issues cannot be easily applied in ship-to-ship inspections because relative motion of the vessels blurs the results over many pixels, significantly reducing system sensitivity. This is particularly true for the smaller watercraft, where passive inspections are most valuable. We have developed a combined gamma-ray, stereo visible-light imaging system that addresses this problem. Data from the stereo imager are used to track the relative location and orientation of the target vessel in the field of view of a coded-aperture gamma-ray imager. Using this information, short-exposure gamma-ray images are projected onto the target vessel using simple tomographic back-projection techniques, revealing the location of any sources within the target. The complex autonomous tracking and image reconstruction system runs in real time on a 48-core workstation that deploys with the system.

1. Introduction

Maritime settings remain among the most challenging arenas for detecting illicit nuclear materials. While considerable progress has been made in addressing nuclear smuggling on large ocean-going vessels and the millions of cargo containers they transport [1], in contrast, relatively little advance has been made in dealing with the smuggling opportunities presented by small vessels. In a study on this issue [1], the Department of Homeland Security points out that there are more than four million small vessels with unencumbered access to 95,000 miles of coastal and inland waterways. While the morphology of ports, bays, and rivers often allows for the use of large passive radiation sensors at navigational choke points [2], the use of passive sensors represents only one aspect of a layered approach. An additional component of an overall system to deal with the small vessel problem includes ship-to-ship inspections. Typically, close inspections are conducted by vessels of modest size (∼9 to 15 m in length), and inclusion of radiation sensors on such vessels is one more layer of an overarching system.

In terrestrial searches for illicit radioactive materials, it has been shown that the use of radiation imaging can increase sensitivity by removing systematic background variations and reducing source confusion issues [3–7]. While radiation background levels are generally lower and less variable in maritime settings, they are still an issue in coastal waters, where many small ship-to-ship inspections occur. Results from detection exercises indicate that variations of up to a factor of two are not unusual. Further, such waters are often crowded, leading to problems of source confusion. Imaging provides the additional benefits of locating a source within a suspect vessel while also providing background-subtracted spectra for source identification. Unfortunately, in ship-to-ship inspections the application of radiation imaging is complicated by the fact that both the inspecting and target vessels are in continuous motion due to wave action. These motions blur radiation images, significantly decreasing the sensitivity of the technique.

To address this problem an approach that relies on automated target-tracking software, using images from visible-light video cameras to determine the relative location and orientation of the two vessels, has been developed. An instrument was constructed

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that uses the tracking information to compensate for the motion by projecting the gamma-ray images into a stationary volume-defined in a coordinate system fixed to the target. This technique digitally removes the motion blur in the gamma-ray images, and with sufficient motion, provides a three-dimensional (3D) tomographic location for a source in the reconstruction volume.

2. Motion measurement

Before the imaging system for use in ship-to-ship inspections was constructed, a study was undertaken to determine the requirements of such an instrument. A small sensor package (Fig. 1) capable of measuring all six degrees of motion of the host vessel was assembled with a three-axis micro-electrical-mechanical system accelerometer [9], and a three-axis rotational sensor and compass [10]. The sensor package was combined with a gyro-stabilized (two-axis) video camera system [8] that could be used to track target vessels. This component also included a Global Positioning System (GPS) device to provide the spatial location and orientation of the host vessel.

The imaging system was deployed aboard a number of local law enforcement vessels in the Los Angeles area, the San Francisco Bay, and the New York–New Jersey harbor, each of which was conducting inspections. The primary results from tests with this system included the field of view required to track the target vessels and, the angular and linear accelerations of the targets in the video images. The data included the motion of the target in the video image, the motion of the host, and the motion of the pan-and-tilt axis of the tracking system. Sample data are shown in Fig. 2.

The outputs from the various sensors were used to generate plots of the field of view needed in the vertical (tilt) and horizontal (pan) directions to contain a full encounter with a target vessel. Results for a number of encounters are shown in Fig. 3.

The primary findings from the measurements were that the vertical and horizontal fields of view needed to be 50° and at least 180°, respectively. The latter field of view requirement was due to different inspection scenarios—particularly one that involved approaching a target vessel, stopping near the vessel during an inspection, and recession from the vessel. In fact, with the relative freedom of motion enjoyed by small vessels, the desired horizontal field of view could be as large as 360°. Based on this requirement, a motorized gimbal system was selected that could provide tracking in the horizontal (pan) direction. Once the mount was motorized, the addition of a motorized tilt axis was a relatively minor addition.

The overall design specifications for the final instrument are given in Table 1. In addition to the axis motion, another primary design consideration was to have a man-portable system that could be assembled and mounted to different host vessels. This required both limiting the mass and using a general-purpose mounting scheme (based on lashing the system to a deck using straps.) In addition, the useful range of operations was limited from near contact (5 m) to a range of 20 m. The range limitation was selected based on the detector system mass limits. Finally, to ease integration of the video and gamma-ray data, an emphasis was placed on maximizing the gamma-ray detector area so that sources could be seen in relatively short exposure times. To maintain a low mass, this meant optimizing the response to low-energy gamma rays.

3. Instrument design

The final instrument, mounted on the back of a patrol vessel, is shown from two angles in Fig. 4. It comprises a coded-aperture gamma-ray camera, a high-definition (HD) stereo video imager, and a two-axis gimbal. More detail on each of these components is given below.

3.1. Gamma-ray imager

The gamma-ray imager is based on a custom commercial Anger camera [11]. The imager uses a 1 cm thick CsI(Na) $28.0 \times 26.5\ \mathrm{cm}^2$ scintillator crystal as the detection element. A full-face exposure of a calibration mask with holes on a 1 cm pitch is shown in Fig. 5. Throughout the life of the project, the system was calibrated several times and the spatial resolution deteriorated during that time (several years). It had an initial lateral spatial resolution at 122 keV of ~3.5 mm full width at half-maximum (FWHM) that degraded to ~6.6 mm FWHM at the last calibration. In general the spatial resolution varies somewhat over the face of the detector, degrading toward the edges as edge effects alter the response of

Fig. 1. Three-axis motion sensor and video camera mounted on the roof of a 33-ft police vessel (arrow on left) and a close-up of the package (right). The black spherical object is the gyro-stabilized video camera of a TASE inertial package [8]; the small box under the support plate on the right contains both a three-axis accelerometer and a magnetometer.