A Dissertation submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

Fusion of Optical Images with Radar Images Constructed using Pulsed Doppler Beamforming to Enhance Object Tracking

Creating a novel five layer image augmented with radial velocity and distance properties

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text. I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student:

Date:

My Contributions

Papers

- Braun, R., Shi, J.: Combining Computer Vision with 1 Dimensional Doppler Radar to provide a low cost robotic vehicle tracking system. In: Proceedings of the 1st Asia-Pacific Conference on Computer-Aided System Engineering, APCAST 2012, p.25
- Shi, J., Braun, R.: Crossed linear arrays using Doppler radar beam-forming for detecting single moving targets. In: Proceedings of the 2nd Asia-Pacific Conference on Computer-Aided System Engineering, APCASE 2014, p.118
- Shi, J., Braun, R.: Image construction using beam forming. In: Proceedings of the 2nd Asia- Pacific Conference on Computer-Aided System Engineering, APCASE 2014, p.121
- Shi, J., Braun, R.: "Crossed Linear Arrays Using Doppler Radar Beamforming for Detecting Single Moving Targets". Book series: Studies Computational Intelligence, Vol. 595, Grzegorz Borowik et al: Computational Intelligence and Efficiency in Engineering Systems, 978-3-319-15719-1, 334637
- Shi, J., Braun, R.: "Image Construction Using Low Cost Airborne Beamforming". Book series: Studies Computational Intelligence, Vol. 595, Grzegorz Borowik et al: Computational Intelligence and Efficiency in Engineering Systems, 978-3-319-15719-1, 334637

Patents

- Provisional Patent - Disclosure DISC-UTS-000433 Radar Enhanced Optical Images
- To be applied for - Sensor minimization using fusion of radar imaging and optical imaging

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Abstract

Target tracking that detects the presence, color, contour, position, velocity, and acceleration is very important in intelligent systems. Single or multiple sensor fusion methods have been developed to improve the tracking quality. There are algorithms to fuse radar and optical images at a decision-making level. However, not many algorithms have been applied to radar image and optical image fusion. This thesis investigates the fusion of these two images. A new five-layer image format is proposed.

Beamforming, a radar signal processing method, has been applied to remote sensing. This suggests the idea that beamforming can be used to create images similar to optical images, with additional information such as range and radial velocity. The radar image can be fused with the optical image to enhance target tracking.

This thesis attempts to prove this proposition. First a tracking system with an optical imaging subsystem and a radar imaging subsystem was designed. Optical images were captured by a high-quality webcam, and radar images were captured by a system designed and built by the author. The radar subsystem is a short-range airborne acoustic radar which contains the transmitter and receiver board, FPGA board and a PC. All the channels need to work simultaneously. The data rate and computation load were very high when the number of sensors increased. For a low-cost development, the resources of FPGA are very limited. Hardware construction is central to this thesis.

Next was the development of a mathematical model of the range layer using pulsed beamforming. The performance with multiple targets was evaluated. The relationship between angle resolution and sensor number was investigated. Linear sensor array beamforming was extended to two dimensions to create the image. It was shown that the targets could be clearly extracted. The required resources increased linearly as resolution improved while on the contrary for a full rectangular array the required resources increased exponentially. Improved image resolution with fewer resources was investigated. Structures included two-line multiplication beamforming, crossed array beamforming, and other sparse structures. Their performances were tested with added noise. Results showed that the algorithms were robust. Sparse rectangular sensor arrays may have ambiguity. The pulsed mode was adopted to detect the distance. A matched filter was used to maximize SNR and minimize false alarms.

In addition to pulsed beamforming, Doppler Beamforming was adopted to provide radial velocity information, which is important for detecting moving objects.

This can remove stationary "clutter" from the image. The performance of linear sensor array beamforming was analyzed for both single and multiple targets. Sensor spacing and angle of arrival were investigated. Then the beamforming was extended to two dimensions. Full rectangular array beamforming, two-line multiplication beamforming, crossed sensor array beamforming and sparse rectangular array beamforming and were studied. FFT filtering methods and filter bank methods were investigated. The processing algorithm and the example image were provided.

Five fusion scenarios for the proposed new image format are discussed.

- Scenario 1 is the fusion of video camera frames with Doppler beamforming radar to enhance moving object detection. The fusion of frame differencing with Doppler beamforming was studied.
- Scenario 2 is using imaging to reduce the ambiguity of crossed array beamforming. The template matching and frame differencing were used to process the region which may contain targets. Then a decision making strategy for reducing ambiguity was introduced.
- Scenario 3 is the fusion of optical imaging with Doppler beamforming radar to enhance tennis ball tracking. The region of interest was marked by the radar. The optical imaging was used to judge the in/out of the tennis ball.
- Scenario 4 is the fusion of optical imaging with pulsed beamforming radar to track a target in 3D position. The Kalman filter was studied and two fusion algorithms were researched.
- Scenario 5 is using Doppler beamforming radar to improve gait analysis. The micro-Doppler characteristics are used to analyze human movement. Then Doppler processing was combined with Doppler beamforming to relate the Doppler frequency to the body part, which can be projected into the optical image.

The experiments show that the creation of a range image layer and a radial velocity image layer are successful. The proposed two extra image layers can be combined with a traditional RGB image to enhance object tracking. The disadvantage is that the data rate is very high when the sensor number is increased. In two dimensional beamforming, there is ambiguity in some shapes of sensor arrays. A sparse rectangular array can be used to reduce the sensor number with fewer ambiguities. The ambiguities can be removed by fusion of different layers in the new image format. The new image format and the fusion algorithms can bring great value to the area of surveillance, sports, medical care and computer-human interaction.