Performance of Super-Resolution Enhancement for LADAR Camera Data

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ABSTRACT
Laser detection and ranging (LADAR) camera systems are increasingly used in robotics applications for autonomous navigation and obstacle avoidance. Their compact size, high frame rate, wide field-of-view, and low cost are key advantages over traditional scanning LADAR devices. However, these benefits are achieved at the cost of spatial resolution. Therefore super-resolution image reconstruction technology can be applied to improve the resolution of LADAR camera data. Previous work by Rosenbush et al. applied the super-resolution algorithm of Vandewalle et al. to LADAR camera data, and observed quantitative improvement in image quality in terms of number of edges detected. This study uses the super-resolution algorithm of Young et al. to enhance the resolution of range data acquired from a commercial available LADAR camera. This work applies a preprocessing stage that increases the accuracy of sub-pixel shift estimation for improved registration of multiple LADAR camera frames and uses the triangle orientation discrimination methodology for a subjective evaluation. The objective is to measure the improvement in probabilities of target discrimination at various ranges achieved by super-resolution enhancement of LADAR camera data.

Categories and Subject Descriptors
D.3.3 [**Image Processing and Computer Vision**]: Enhancement – *Filtering, Registration.*

General Terms
Algorithms, Performance, Human Factors

Keywords
Super-resolution, LADAR camera, image registration, triangle orientation discrimination methodology

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1. INTRODUCTION
Laser detection and ranging (LADAR) is a crucial component for navigation in autonomous or semi-autonomous robots. Current small robots generally employ a 2D scanning LADAR that scans along a single line and therefore cannot detect objects above or below the detection line [1, 2]. In indoor urban environments where the setting is highly cluttered with overhanging objects such as tabletops, the 2D scanning LADAR systems may not be sufficient for navigation and obstacle avoidance [1]. A new generation of small and compact 3D LADAR devices, named LADAR camera, offers a promising solution to small robot navigation in urban environments where modern warfare is often conducted.

LADAR camera devices are compact and lightweight sensors that acquire a 3D range image of the surrounding environment. The SR-3000[1] LADAR camera device

Figure 1. SR3000 Error! Bookmark not defined. **LADAR Camera**

[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment identified are necessarily best for the purpose.

(Figure 1) used in this study weighs 162 g and measures (5.0 x 6.7 x 4.23) cm [3]. LADAR camera devices emit diffuse modulated near-infrared light and measure the subsequent phase shift between the original emitted light and the reflected light. The phase measurements are combined to calculate the range data based on the time-of-flight principle [3]. The detector utilized by LADAR camera devices is a focal plane array (FPA), which is typically limited to a maximum size of (256 x 256) detectors. Consequently, these devices cannot achieve the resolution of scanning LADAR systems. This disadvantage of LADAR camera systems may be rectified by the application of super-resolution image reconstruction.

Super-resolution algorithms utilize a series of low-resolution frames containing sub-pixel shifts to generate a higher resolution image. These algorithms are typically composed of two major stages: registration stage and reconstruction stage. During the registration stage, the shift with respect to a reference frame (usually the first frame of the series) is computed to sub-pixel (i.e. decimal pixel) accuracy. The second stage utilizes this sub-pixel information to interpolate the low-resolution frames onto a higher resolution grid. A necessary condition for successful super-resolution enhancement is the presence of differing shifts between the frames in the series. The differing shifts of each frame provide additional information from which to reconstruct the super-resolved imagery. Previous work by Rosenbush et al. [4] applied a super-resolution algorithm [5] to LADAR camera data, and observed improvement in image quality in terms of number of edges detected. In this work, the super-resolution algorithm of Young et al. [6] is applied to LADAR camera imagery. This algorithm separates the registration stage into a gross shift (i.e. integer pixel shift) estimation stage and a sub-pixel shift (i.e. decimal pixel shift) estimation stage for improved registration accuracy. Both sub-stages use the correlation method in the frequency domain to estimate shifts between the frame series and the reference image. The reconstruction stage of Young et al.'s algorithm applies the error-energy reduction method with constraints in both spatial and frequency domains to generate a high-resolution image [6]. Because LADAR camera imagery is inherently smoother than visible light imagery (LADAR camera data does not capture the texture or color of the scene), this work develops a preprocessing stage for improved image registration. Specifically, a wavelet edge filtering method [7] and a Canny edge detection method [4] are investigated and compared against the accuracy achieved with no preprocessing. The wavelet edge filtering method provided more accurate shift estimation for LADAR camera data.

To assess the improvement in super-resolution enhanced LADAR camera data, the authors conducted perception experiments to obtain a human subjective measurement of quality. The triangle orientation discrimination (TOD) methodology [8,9] was used to measure the improvement achieved with super-resolution. The TOD task is a four-alternative forced-choice perception experiment where the subject is asked to identify the orientation of a triangle (apex up, down, right, or left) [9]. Results show that the probability of target discrimination as well as the response time improves with super-resolution enhancement of the LADAR camera data.

2. METHODOLOGY

2.1 Preprocessing Stage

The purpose of the preprocessing stage is to emphasize LADAR camera image edges for improved frame registration. One investigated method was the use of multi-scale edge-wavelet transforms [10] to calculate the horizontal and vertical partial derivatives of the input image at the second wavelet scale for each frame of the series. The two derivatives were then combined using sum of squares to produce a wavelet edge enhanced frame series. Another investigated method was the use of Canny edge detection algorithm to generate binary edge frame series.

To assess the benefit of preprocessing, the following procedure was followed. A synthetic frame series was generated with known sub-pixel shifts. First, an oversampled non-aliased scanning LADAR reference image (204 x 204) pixels was interpolated by an upsampling factor of eight (1632 x 1632) pixels using a Fourier windowing method [10]. Then, the simulated high-resolution image was sub-sampled at different factors to produce several low-resolution frame series, each with a different degree of aliasing. Figure 2 shows the un-aliased spectrum of a discrete space signal (e.g. scanning LADAR image) produced by oversampling a continuous space signal at a sampling frequency greater than the Nyquist frequency. If the sampling frequency is below Nyquist (simulated by sub-sampling the oversampled image), the spectrum of the sampled signal is aliased with distorted higher frequency components as depicted in red in Figure 2.

Synthetic frame series was generated by sub-sampling every m pixels in both dimensions of the simulated high-resolution image, where m = 4, 8, 12, 16, 20, 28, 36, 48, 56. Therefore the undersampling factors are $m/8$ (i.e., 0.5, 1, 1.5, 2, 2.5, 3.5, 4.5, 6, 7), simulating different degrees of aliasing. For each undersampling factor, the sub-pixel shifts for each frame of the synthetic series were generated by varying the starting pixel position of sub-sampling according to a uniform random distribution (30 frames for each series). Then preprocessing using either the wavelet or Canny method was performed. Sub-pixel shift estimates from the preprocessed and no preprocessing series were compared to the known shifts. Let $\varepsilon_i = (\varepsilon_{xi}\ ,\ \varepsilon_{yi})$ denote the registration error vector of the i^{th} frame where ε_{xi} and ε_{yi} are the registration errors in the x and y directions. A mean absolute error (MAE) can be calculated for the frames of each synthetic series using the following equation:

$$E = \frac{1}{n}\sum_{i=1}^{n}\|\varepsilon_i\| = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\varepsilon_{xi}^2 + \varepsilon_{yi}^2}$$

where $n = 30$. The registration errors of the wavelet preprocessing method was compared to that of Canny and no preprocessing methods to assess the accuracy at each undersampling factor.

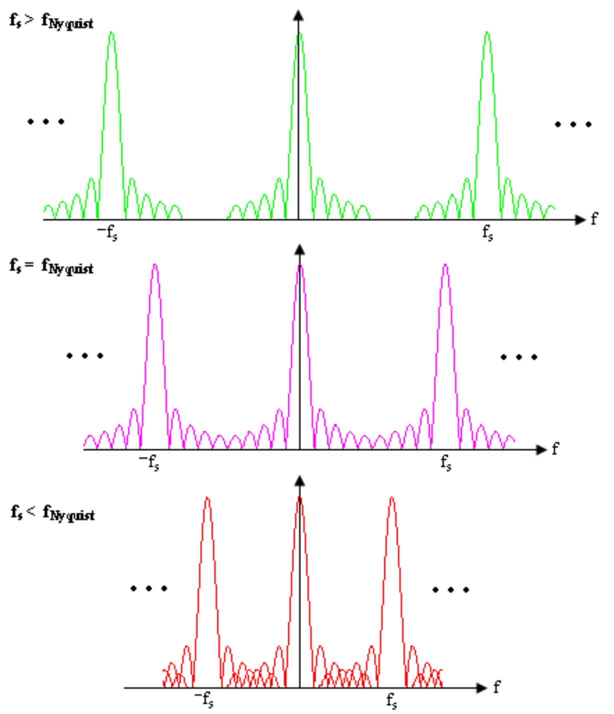

Figure 2. (Top) Un-aliased spectrum of signal sampled above Nyquist frequency, (mid) at Nyquist, and (bottom) aliased at below Nyquist frequency.

2.2 Triangle Orientation Discrimination (TOD) Methodology

The TOD methodology, developed by Netherlands TNO Physics and Electronics Laboratory (TNO-FEL), is a perception study that allows human subjects to provide a measure of image quality at various target ranges [9]. The test pattern is an equilateral triangle in one of four possible orientations (apex up, down, left, or right), and the measurement process is a four-alternative forced-choice psychological procedure that requires the observer to indicate the orientation. Variation of triangle contrast/size by changing target ranges results in a correct discrimination percentage between 25 % (pure guess) and 100 %. Probabilities of target discrimination at different ranges can then be calculated to measure the quality of both the original and super-resolved data.

The TOD method is suitable for electro-optical and optical imaging systems, and has been widely used in thermal and visual domain imagers. This methodology provides a simple task that has a close relationship to real target acquisition, and the results are free from observer bias [8,9]. The TOD methodology was adapted to LADAR camera data by using a target consisting of a square white foam board target (50 x 50) cm with an equilateral triangular hole (7.5 cm per side) cut into the board as shown in Figure 3. The triangular hole provides the necessary depth contrast against the board.

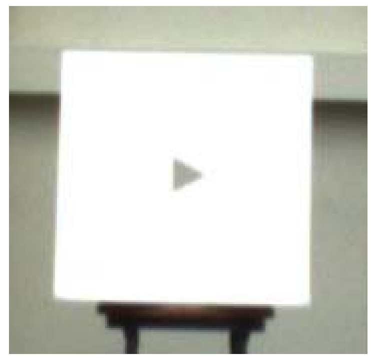

Figure 3. TOD setup

2.3 LADAR Camera

The device utilized in this study is the SwissRanger SR-3000**Error! Bookmark not defined.** LADAR camera. The camera emits diffuse 850 nm near-infrared light modulated at a default frequency of 20 MHz from a bank of 55 light emitting diodes. The non-ambiguity range achieved at this modulation frequency is 7.5 m. The SR-3000**Error! Bookmark not defined.** has a pixel array of 176 x 144 with a field-of-view of 47.5° x 39.6°, and can capture images at a maximum rate of 50 frames/s (variable with respect to the integration time setting).

2.4 Data Collection

Data collection for the experiment was conducted at a laboratory in the National Institute of Standards and Technology. The SR-3000**Error! Bookmark not defined.** LADAR camera was placed 6.5 m from a beige wall as depicted in Figure 3. The target was positioned at (3, 3.5, 4, 4.5, 5, 5.5, and 6) m from the camera. The investigated ranges were limited to between (3 and 6) m because inaccurate behavior of LADAR cameras was observed at very close and very far target distances [11]. At each range, the triangle was positioned at one of four possible orientations (apex up, down, left, right) with the center approximately 1 m high. For each orientation at each range, four trials were conducted. Each trial consisted of a sequence of 32 frames acquired by holding the camera. The natural motion of the hand while holding the camera provided the shifts required for the super-resolution algorithm. Motion is assumed to be limited to translations in the x (horizontal) and y (vertical) planes. Though slight rotation and translation in the z-plane (depth) might have occurred from holding the camera, these parameters were not considered in the current study.

2.5 Data Processing

For each series of 32 frames, the first 25 frames are utilized for super-resolution image reconstruction. The first frame was used as the reference frame from which pixel shifts were calculated for successive frames. The use of 25 frames resulted in a resolution improvement factor of five in each direction for the super-resolved image. To ensure that the monitor modulation transfer function (MTF) was not a limiting factor in the experiment, the super-resolved images (250 x 250 pixels) were bilinearly interpolated by a factor of two to 500 x 500 pixels. The original imagery (50 x 50 pixels) was bilinearly interpolated to 500 x 500 pixels for consistency between the baseline and super-resolved imagery.

2.6 Perception Experiment

The perception experiment was a four-alternative forced-choice procedure (up, down, left, right). The imagery in this experiment was organized in the image cells and their naming convention is shown in Table 1. As shown in the row of original images in Table 1, the grayscale baseline range imagery was grouped into seven cells corresponding to the seven different target ranges. Each cell consisted of 16 original low-resolution LADAR camera images (4 orientations x 4 trials). Similarly, the grayscale super-resolved range imagery was grouped into seven cells consisting of 16 images each as shown in the row of super-resolved images in Table 1. The experiment therefore consisted of 14 cells with a total of 224 images.

Range m	A 3.0	B 3.5	C 4.0	D 4.5	E 5.0	F 5.5	G 6.0
Original Image	AA	BA	CA	DA	EA	FA	GA
Super-resolved image	AB	BB	CB	DB	EB	FB	GB

Table 1. Image cell format and naming convention

Nine subjects participated in the experiment in July 2008. The subjects were shown one image at a time with randomized presentation of cells and randomized presentation of images within each cell. The display was a 19 inch flat panel (Dell 1908FP**Error! Bookmark not defined.**) with a resolution of 1280 x 1024 pixels.

3. RESULTS AND DISCUSSION

3.1 Assessment of Registration Accuracy

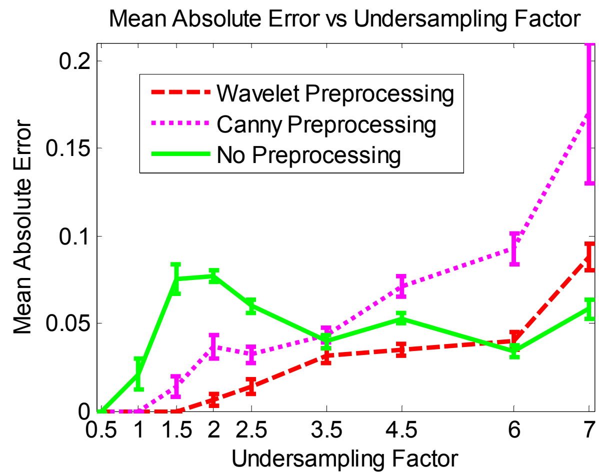

Figure 4. Mean absolute registration error with standard deviation for each undersampling factor.

Figure 4 shows the mean absolute error of registration at each undersampling factor for the generated synthetic experiments. The unit of error is fraction of a pixel. Wavelet preprocessing outperformed both the Canny method and no preprocessing method for undersampling factors of less than 6. Wavelet preprocessing was especially effective at low and moderate degrees of aliasing (undersampling factor of less than 3.5). If the imagery contained severe aliasing (undersampling factor greater than 6), then no preprocessing resulted in higher registration accuracy. The observed trend is expected. LADAR camera data is characteristically smooth due to the lack of texture information, so edge filtering with the wavelet method will improve registration. But if the data is severely undersampled that its mid to high frequency components are corrupted by aliasing, then wavelet edge filtering (which uses these severely corrupted frequency components) will result in poorer registration. The degree of aliasing in the imagery acquired with the SR-3000**Error! Bookmark not defined.** is expected to be in the moderate range as super-resolved imagery using wavelet preprocessing yields fewer artifacts than imagery produced without preprocessing.

3.2 Triangle Orientation Discrimination Perception Experiment

Figure 5 shows grayscale and color images (color-coded to distance) of the TOD target oriented up at a distance of 5 m from the camera. The orientation of the equilateral triangular hole is difficult to discern in the original images at this distance as the triangular hole appears like a blurred circle. By contrast, the orientation is clear in the super-resolution enhanced imagery. For imagery with target distances greater than 5 m, the orientation, as expected, was still more difficult to discern using the original LADAR camera imagery. But super-resolution at these greater distances proved to be effective.

(a) original **(b) super-resolved**

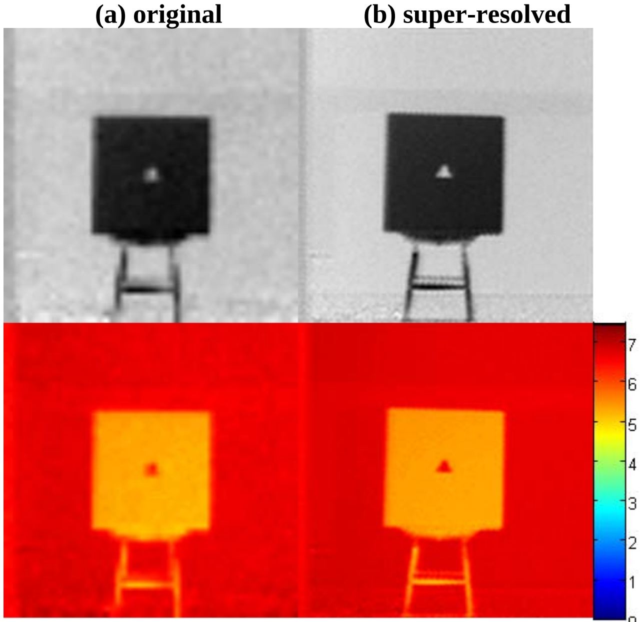

Figure 5. Grayscale (top) and color-coded (bottom) LADAR camera imagery for (a) original image and (b) super-resolved image of TOD target at 5 m.

Figure 6 shows grayscale and color images of the TOD target oriented left at a distance of 4 m from the camera. As the target distance decreases, the orientation of the triangular hole becomes more visible in the original imagery, though the triangular hole still appears distorted. In the super-resolved image, the triangular hole does not appear distorted, and is shaped more like a triangle.

Figure 7 shows the group-averaged chance-corrected probability of target discrimination at each target range. At all ranges, super-resolved imagery produced a higher probability of target discrimination with smaller inter-subject variability. At a target distance of 3 m, the original imagery had a 77 % of the probability of target discrimination, while the super-resolved imagery reached 100 %. The target discrimination performance is increased by 30 % using the super-resolution algorithm. As the target distance increased, subjects had more difficulty to discriminate the target orientation. At a target distance of 6 m, the original imagery had a 20 % of the probability of target discrimination, while the super-resolved imagery reached 90 %. That is a 350 % improvement in target discrimination performance. In summary, the probability of target discrimination is increased by 30 % to 350 % for the target ranges from 3 m to 6 m using the super-resolution algorithm.

(a) original **(b) super-resolved**

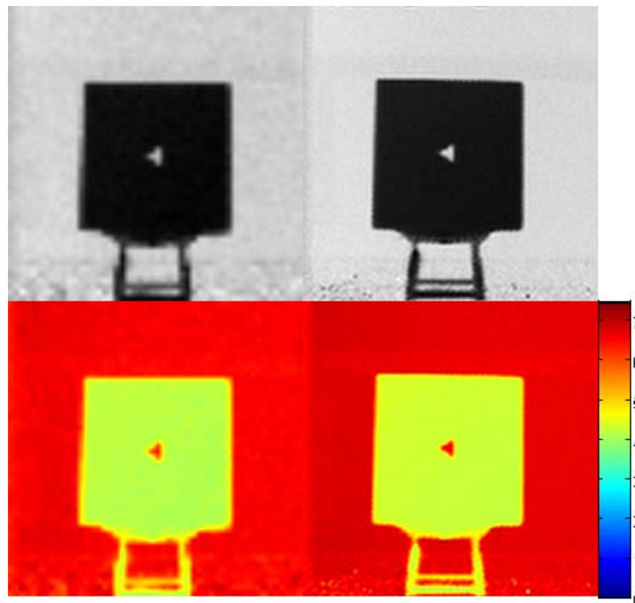

Figure 6. Grayscale (top) and color-coded (bottom) LADAR camera imagery for (a) original image and (b) super-resolved image of TOD target at 4 m.

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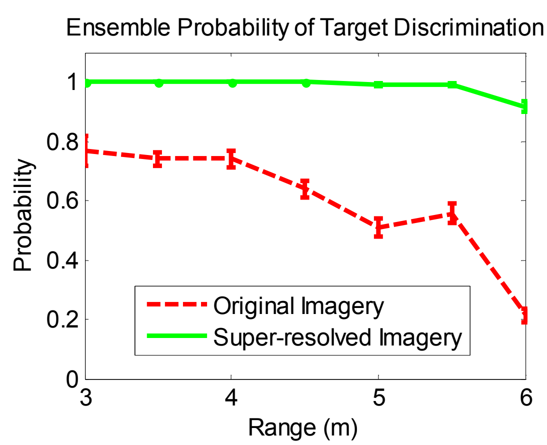

Figure 7. Chance-corrected probability of target discrimination at each target range.

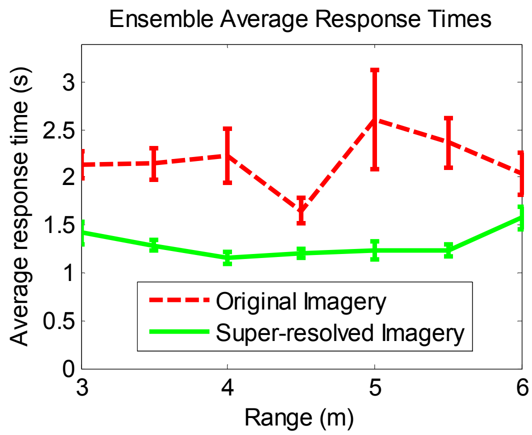

Figure 8. Response times at each target range with standard error bars showing inter-subject variability.

Not only were subjects able to achieve higher accuracy at all ranges with super-resolved imagery, but the response times were also faster with less variability for super-resolved imagery at all ranges. Figure 8 shows the group-averaged response times at each range with standard error bars representing inter-subject variability. At a range of 6 m, subjects responded in an average time of 1.58 s using the super-resolved imagery, 23 % faster than the response time using original imagery.

4. CONCLUSION

Super-resolution image reconstruction is complemented by a wavelet preprocessing stage for improved image registration, yields significant benefits for LADAR camera imagery. In the triangle orientation discrimination experiment, subjects achieved higher accuracy at all investigated target ranges with faster response times and reduced inter-subject variability for super-resolved imagery. Complemented by super-resolution image reconstruction, the high frame rate, small size, and light-weight LADAR camera sensors will be ideal for autonomous or semi-autonomous robot navigation in urban indoor environments. In semi-autonomous robot navigation, super-resolution enhancement will provide human operators with increased target discrimination. In fully autonomous mode, super-resolved imagery will allow guidance software to improve obstacle avoidance. The incorporation of super-resolution into the US Army's robotic applications will improve small robot performance, contributing to the soldier's survivability and lethality.

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