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Inter-Frame Smart-Accumulation Technique for Long-Range and High-Pixel Resolution LiDAR

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To realize 200-m-range 0.1-degree-angular-resolution LiDAR, which is essential for a reliable self-driving, we propose advanced SAT (Smart Accumulation Technique [1]) algorithm, Inter-frame SAT (I-SAT). I-SAT adds only the returned peaks as distance candidates, within the time window estimated from the distance of the previous frame and the target's motion. Compared to conventional methods that directly average the distance or the ADC results of the previous frame, I-SAT can enhance both a measurable distance and an angular resolution, while reducing both the hardware penalty and measurement errors due to target motion. According to the simulation and measurement results, I-SAT improves long range resolution by more than 2x and increases measurable range with the same resolution by 22% compared with SAT and de-noising [3]. The hardware penalty is only 2% of conventional ADC averaging. (Keywords: LiDAR, de-noising, and averaging)

Since autonomous driving needs to detect motorcycles and small obstacles located in the distance, LiDAR systems must have long-range and high angular-resolution capabilities, typically ~0.1 degree in 200m. For long-range measurement, Smart Accumulation Technique (SAT) has been developed. SAT recognizes and selectively accumulates target reflection data by using intensity of signals and background light information and enables measurement in low S/N ratio conditions. Furthermore, an algorithm that performs de-noising and selects appropriate data among multiple returns based on "reliability" has been proposed [3]. Here, reliability (R2) is provided with intensity Li (accumulated intensity divided by accumulation count), distance Di of pixel i and accumulation scope A, as follows (for a single return):

$$R2_i = \left[\sum_{j\in A} L_j^2 \times p(i,j)\right]^{\frac{1}{2}},\ \ p(i,j): \left|D_j - D_i\right| \le k \tag{1}$$

Using reliability resolves a problem of range-value clustering, a side effect of averaging, and enables long-range measurement with few false data points. However, pixel and angular resolutions in the horizontal direction of the results are 240 pixels and 0.19 degree respectively for instance [1][2], which should be improved by about a factor of two.

Although conventional averaging methods accumulate ADC results within the present frame only [1][2][3][4][5], using information from the previous frame would obtain better performance. On that point, the first option is to average range results of the present and previous frames directly [6], which will often cause incorrect results when the target is moving. Accumulating ADC results of the present and previous frames together is another option, but has two problems. The first problem may lead to incorrect measurement by relying on old results, although some improvement is expected compared with the direct averaging. The second problem is that the procedure requires an enormous amount of memory to preserve all the ADC results of previous frames. An algorithm to estimate location and velocity using data of previous frames was presented [7], but it does not aim at improving performance by averaging and is not a solution for the above problems.

To resolve the problems, we propose a new averaging algorithm which does not preserve and accumulate ADC results of previous frames. The algorithm preserves range results instead of ADC results. It defines search windows according to the distance and motion measured in the previous frame and selects additional output candidates from returns (peaks) detected within the windows in the present frame, which indirectly utilizes previous-frame information. As illustrated in Fig. 1, conventional SAT chooses the two largest peaks as output candidates in accumulated results of the present frame. The method proposed here determines search windows based on previous-frame data and adds two more candidates detected in the windows, the third and fourth peaks, as shown in Fig. 2. Please note that no peak exists in Window 1, which has no influence on measurement and does not cause a false result. Among the candidates, ISAT selects peaks according to a new reliability R3 which is extended to include information from the previous frame.

Extended reliability is formulated as shown in (2)-(4):

$$R3_{i,a} = \sqrt{{R2_{i,a}}^2 + {RP_{i,a}}^2} \quad \text{i: ID for target pixel, a: ID for return (peak)} \tag{2}$$

$$R2_{i,a} = \left[\sum_{j\in A, b\in Ss(j)} L(\mathrm{j,b,N})^2 \times P_s\big(D(i,a,N), D(j,b,N)\big)\right]^{1/2}, P_s(D_1, D_2): |D_1 - D_2| \le k_s(D_1) \tag{3}$$

L: luminance intensity-ambient intensity, N: present frame, N-1: previous frame, Ss(j): set of peaks of pixel j in present frame,

Ps: function to judge whether two distances are the same, $k_s(D) = max(const \times D, lowerbound)$

$$RP_{i,a} = \left[\sum_{j \in B} L(j, b, N-1)^2 \times P_p(D(i,a,N), D(j,b,N-1), \Delta D) \times \left\{1 + P_p\left(D(j,b,N-1), D\left(j, b^{\prime}, N-2\right), \Delta D\right)\right\}\right]^{1/2}$$

$$P_p(D_1, D_2, \Delta D_2): |D_1 - D_2 - \Delta D_2| \leq k_p(D_1, \Delta D_2), k_p(D_1, \Delta D_2) = k_s(D_1) + const \times \Delta D_2 \quad (4)$$

B: set of pixels searched for previous-frame information (including pixel i), b/b': the most reliable peak in previous/ 2nd preceding frame

Here, R2 is the same as in (1) and provides a pure contribution of the present-frame results to reliability. RP presents a newly-added contribution originating in previous-frame and the 2nd preceding frame information. Pp in (4) is a function to define a search window which is determined by a distance D and its change ΔD obtained in the previous frame. Here, ΔD expresses the difference between distances of the previous frame and the 2nd preceding frame, which means the motion of the object. The smaller the velocity is, the narrower the window and the smaller the influence of ambient light should be.

Equation (2) assumes that the range results and intensities of signal peaks and ambient light of the previous frame are preserved. When only range results of the previous frame can be used, reliability is formulated approximately as shown in (5):

$$R4_{i,a} = RS_{i,a} \times \sqrt{\left(1 + Q_p/Q_s\right)} \quad (5)$$

$$Q_s = \sum_{j \in A, b \in Ss(j)} F_s\big(D(i,a,N), D(j,b,N)\big), Q_p = \sum_{j \in B, b \in Sp(j)} F_p\big(D(i,a,N), D(j,b,N-1)\big) \quad (6)$$

Fig. 5 shows experimental results of a range image, where (b) and (c) show results of the conventional SAT/R2 and the proposed method, ISAT/R3, respectively. As shown in Fig. 5, range image (c) has fewer black regions corresponding to failure of measurement than range image (b). Fig. 3 indicates the relationship of the range and success ratio given by the LiDAR-system simulator. As shown in this figure, use of previous-frame information improves measurable distance by ~22%; here, measurable distance is defined as the distance at which the success ratio is equal to 90% with 99% de-noising. Fig. 4 shows the relationship of the number of candidates and their measurable distance, and Fig. 6 shows the relationship of the number of candidates and resolution at 205m that corresponds to the measurable distance of the conventional approach. Here, the dotted blue line indicates results of the conventional method (SAT+R2) where the number of selected candidates increases from one to four based on present-frame information only. The solid red line indicates the results of the proposed method (ISAT+R3) using previous-frame information. Fig. 4 suggests that candidates based on previous-frame information and reliability R3 contribute to the improvement of measurable distance. As shown in Fig. 6, the proposed method increases resolution at long-range by x2.2. These results mean that the method can detect smaller objects (ex. motorcycles) at the same distance and the same object (ex. cars) at a longer distance.

This algorithm can be implemented with additional hardware of 0.33 mm^2 in 28 nm process technology (33% of SAT implementation) for 450(H) x 192(V) frame size. The additional hardware to SAT consists of 1.73 MB memory and 50 KG logics. The memory size is quite small (1.8%) compared to 95 MB, the size of ADC data from the previous frame. It is obvious that not preserving ADC data of the previous frame plays a critical role in implementing the inter-frame algorithm with a moderate area penalty.

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[7] US Patent No.: US 7,895,007

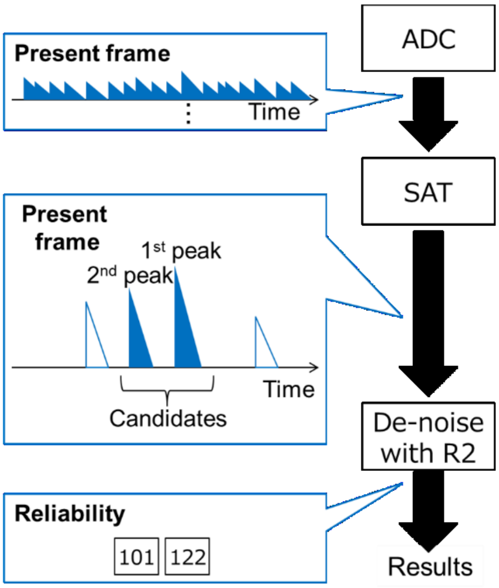


Fig. 1 Conventional method

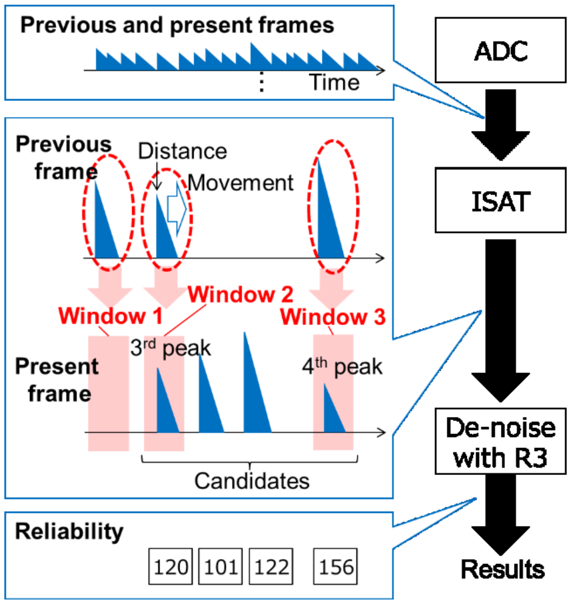
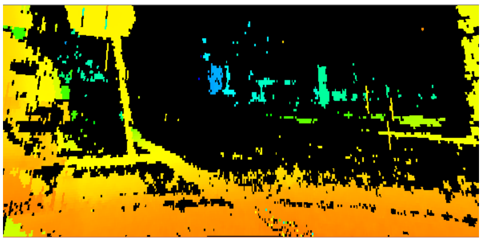
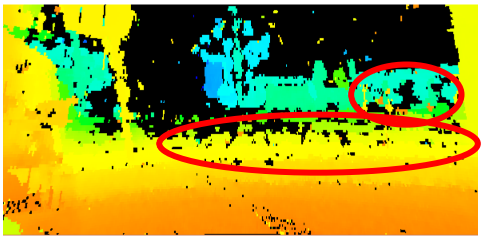


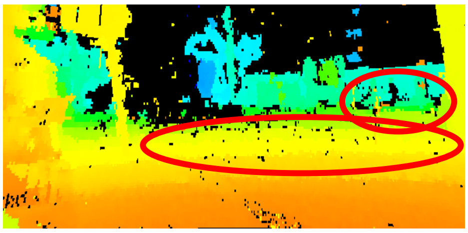
Fig. 2 Proposed method



(a)SAT＋intensity-de-noise (conventional)



(b)SAT+R2 (conventional)



(c)ISAT+R3 (proposed method)

Fig. 5 Example of range images

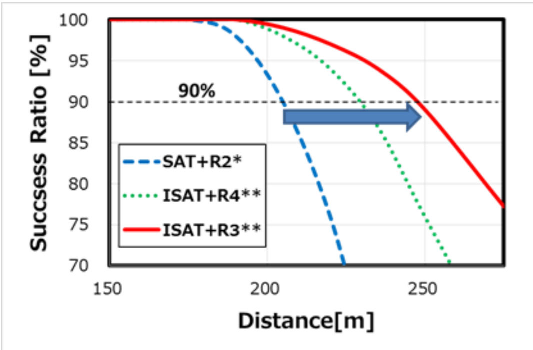


Fig. 3 Success ratio (simulation result)

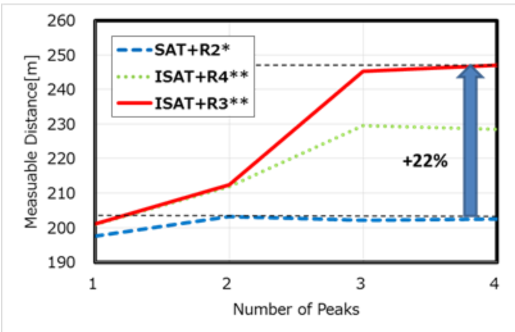


Fig. 4 # of Candidates vs measurable range

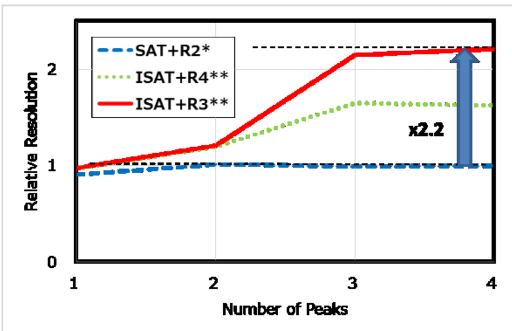


Fig. 6 # of Candidates vs relative resolution

Simulation condition for Fig.4 – 6

・ Success: range error ≦ 1% of range value
・ Reflection rate of target: 10%, no back ground
・ LD Power: 108mW
・ Resolution: 450 x 178 x 20 fps
・ Intensity of ambient light: 100 K lux

* 4 candidate peaks on present frame

** 2 candidate peaks on present frame and 2 candidate peaks on previous frame